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THE PHOTONICS DESIGN & APPLICATIONS HANDBOOK®

THE
OPTICAL
INDUSTRY & SYSTEMS
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DIRECTORY®**

The International Handbook
and Reference to Photonics:
High-Technology Optics,
Electro-Optics, Lasers, Fiber
Optics and Imaging

In This Book:

- Graphs, Charts, Schematics
- Product Specification Tables
- Conversion Tables
- Design Articles

1986



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Digital Delay Generators provide accurate, repeatable control of time. DDGs are a source of stable intervals, pulses, impulses and gates produced as low-jitter outputs for precise triggering, gating, syncing, delaying, blanking, calibrating, etc. Remote IEEE-488 or BCD programmability is available.

Internal or external triggering of a DDG produces a pair of fast risetime pulses, T_0 (Initial Pulse) and T_1 (Delayed Pulse), from separate outputs. The delay can be the selected interval between T_0 and T_1 or, by adding the insertion delay, T_1 can be timed from an external event trigger.

A Gate is a third output equal to the delay. With the Model 7085, both T_1 's delay and width are digitally selectable and can be auto-swept internally from RAM-stored time settings.

Accuracies and jitter of 100 ps or less are attainable. Pulse amplitudes of +5 V and -1 into 50 Ω are standard; the 7085 and 7095 also have complement and ECL outputs. Trigger amplifiers can boost pulses to 250 V. Model AP-3 portable or TB-4 rack/bin power supply house the modular units. Key specs are below. Phone (415) 527-1121 to discuss your applications or get detailed literature.

MODEL	Time Resolution	Basic Time Range	Optional Time Range	Insertion Delay	Indeterminacy	Basic Jitter (RMS)	Trigger Rate	Input Sensitivity	Operating Modes	Power Requirements	Base Price (USA)
7095	50 ps	0-10 μ s	0-10 ms ¹	65 ns	None	30 ps	0-10 MHz	200 mV	D,G,I	115/230 VAC	\$6900
7030A	1 ns	0-100 μ s	—	80 ns	None	50 ps	0-10 MHz	250 mV	D,G	± 6 , ± 12 , -24V	\$3670
7065	1 ns	0-1 ms	0-1 s ¹	85 ns	None	50 ps	0-5 MHz	200 mV	D,G	115/230 VAC	\$4970
7075	1 ns	0-1 ms	0-1 s ¹	85 ns	None	50 ps	0-5 MHz	200 mV	D,G	115/230 VAC	\$5685
7085	1 ns	0-100 ms ²	—	150 ns	None	50 ps	0-5 MHz	200 mV	D,W	115/230 VAC	\$7500
7050	10 ns	0-10 ms	0-1 s ¹	55 ns	± 5 ns	100 ps	0-5 MHz	200 mV	D,G,P	± 6 V	\$2565
7055	10 ns	0-10 ms	0-1 s ¹	55 ns	± 5 ns	100 ps	0-5 MHz	200 mV	D,G,P	115/230 VAC	\$3250
7020	100 ns	0-10 ms	0-10 s ¹	110 ns	± 50 ns	100 ps	0-1 MHz	100 mV	D,G	± 6 , ± 12 V	\$1735
7010	100 ns to 1 ms	0-10 ms to 0-100 s ³	—	120 ns	± 50 ns	500 ps	0-1 MHz	2V	D,G,P, E,B ⁴	115/230 VAC	\$1235

Operating Modes: D — Delay; G — Gate; I — Impulse; D/W — Delay/Width; P — Period; E — Events; B — Burst.

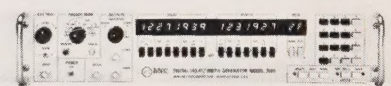
Notes: ¹Option A. ²Width of Delayed Pulse also selectable in 1 ns steps to 10 ms. ³Selectable in 5 decade steps. ⁴With Option B.



MODEL 7075



MODEL 7010



MODEL 7085

Light Pulse Generators are an optical waveform equivalent of electronic pulse generators. Blue, green, red or infrared outputs are available. LPGs serve as a basic tool for electro-optics work. Variable are the light output's rep rate, pulse

width, delay and power. Features include fast transition times, adjustable peak amplitude control, CW output, external drive or modulation and more. See key specs below. Call (415) 527-1121 to talk about needs or for literature.

MODEL	Wavelength	Spectral Width	Peak Power	Power Range	Maximum Rate	Rate Stabilized	Risetime	Stabilized	Operating Modes	Price (USA)
6010A	660 nm	± 30 nm	50 μ W	20 dB	20 MHz	500 kHz	10 ns	900 ns	S,D,C,R	\$2545
6010B	820 nm	± 20 nm	200 μ W	20 dB	20 MHz	500 kHz	10 ns	500 ns	S,D,C,R	\$2545
6010C	560 nm	± 30 nm	3 μ W	20 dB	2 MHz	250 kHz	50 ns	900 ns	S,D,C,R	\$2545
6010D	490 nm	± 45 nm	300 nW	10 dB	2 MHz	150 kHz	75 ns	2 μ s	S,D,C,R	\$2950
6010E	850 nm	± 20 nm	200 μ W	20 dB	20 MHz	200 kHz	10 ns	500 ns	S,D,C,R	\$2545
6020	830 nm	± 1 nm	2 mW	20 dB	—	250 MHz	—	1 ns	S,D,C,R,M,Q,I	\$8250
6030	1300 nm									

Scheduled for 1986

Operating Modes: S — Single Pulse; D — Double Pulse; C — CW; R — Ext. Drive; M — Ext. Modulation; Q — Square Wave; I — Impulse.



MODEL 7030A



MODEL 7050



MODEL 6010



MODEL 6020

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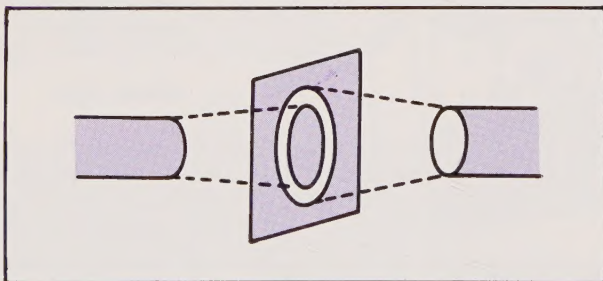
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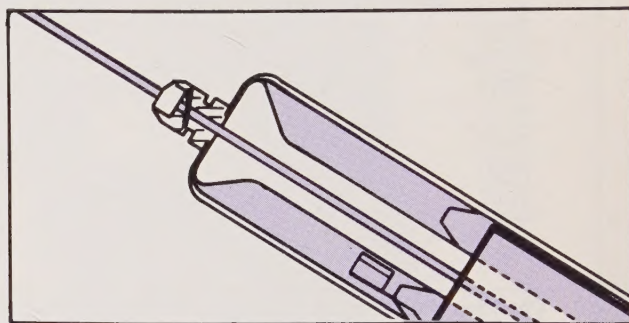
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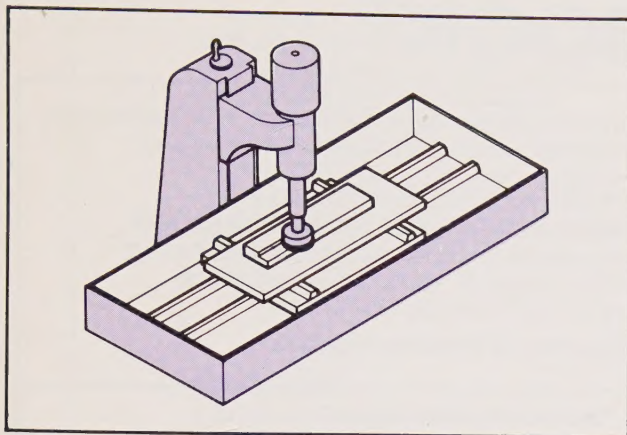
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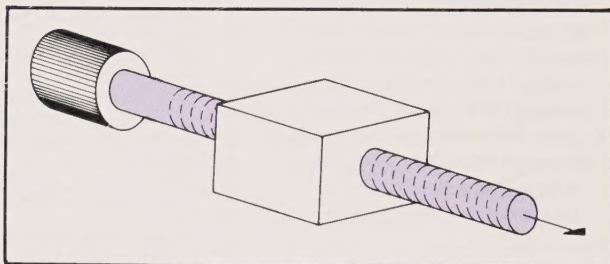
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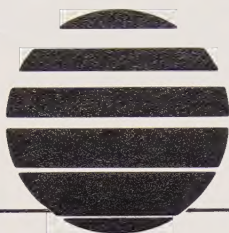
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To: YOU

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In order for our industry to take maximum advantage of the tremendous opportunities in the future, and for the individual companies within our industry to meet the period of growth facing them, we must build a strong and efficient superstructure—one in which communication and cooperation prepare us for our common success.

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Physical Constants & Conversion Factors

LENGTH [L]

1 M = 39.3700 IN = 3.280833 FT = 1.093611 YD
 1 KM = 0.62137 MI = 0.53996 NAUTICAL MI (INTERNATIONAL)
 1 MICROMETER (μ M) = 10^{-6} M = 10^{-4} CM = 10^4 A = 39.3700×10^{-6} IN
 1 NANOMETER = 10^{-7} CM = 10^{-9} M = 10^{-3} μ m = 10A
 1 ANGSTROM (A) = 10^{-8} CM = 10^{-10} M = 10^{-4} μ m = 3.937×10^{-9} IN
 1 IN = 1000 MILS = 2.540005 CM
 1 FT = 30.48006 CM = 1.89394 $\times 10^{-4}$ MI
 1 YD = 0.91440183 M
 1 FATHOM = 6 FT = 1.828804 M
 1 STATUTE MILE = 1760 YDS = 5280 FT = 6.3360 $\times 10^4$ IN = 1.60935 KM
 = 0.868979 NAUTICAL MI (INTERNATIONAL)
 1 LIGHT YEAR = 5.8804 $\times 10^{12}$ MI = 9.4637 $\times 10^{12}$ KM = 0.307 PARSECS
 1 NAUTICAL MI (INTERNATIONAL) = 1852 M = 6,076.10333 FT = 1.15078 MI

AREA [L²]

1 CM² = 10^{-4} M² = 10.764 $\times 10^{-4}$ FT² = 0.15500 IN²
 1 KM² = 0.3861006 MI² = 247.1044 ACRES
 1 CIRCULAR MIL = AREA OF CIRCLE 1 MIL IN DIAMETER
 = 0.78540 SQ MIL = 10^{-6} CIRCULAR IN
 1 IN² = 6.4516258 CM² = 1.27324 $\times 10^6$ CIRCULAR MILS
 1 YD² = 9 FT² = 0.83613 M²
 1 MI² = 3.0976 $\times 10^6$ YD² = 640 ACRES = 2.589998 $\times 10^6$ M²
 1 ACRE = 43,560 FT² = 10 SQ CHAINS = 4046.873 M²

VOLUME [L³]

1 CM³ = 0.061023 IN³ = 0.03381 FL OZ
 1 LITER = 1000.027 CM³ = 33.8147 FL OZ = 1.05671 QT.
 (LIQUID) = 0.26418 GAL
 1 FT³ = 1728 IN³ = 28.317 LITERS = 7.481 GAL = 0.80357 BUSHEL
 1 GAL = 231 IN³ = 0.13368 FT³ = 3.78533 LITERS
 1 QT = 32 FL OZ = 946.33 ML
 1 PT (LIQUID) = 0.5 QT = 28.875 IN³ = 1.042 LB WATER AT 62°F
 1 FL OZ = 1.042 OZ AVOIRDUPOIS (AV) WATER AT 62°F

TIME [T]

1 WEEK = 7 DAYS = 168 HOURS = 10,080 MIN = 604,800 SEC
 1 MEAN SOLAR DAY = 1440 MIN = 86,400 SEC
 1 CALENDAR YEAR = 365 DAYS = 8760 HR = 5.256 $\times 10^5$ MIN = 3.1536 $\times 10^7$ SEC
 1 SIDEREAL YEAR = 365.256 DAYS (MEAN SOLAR) = 8766.14 HRS (MEAN SOLAR)

VELOCITY [LT⁻¹]

1 M/SEC = 2.2369 MI/HR
 1 MI/HR = 1.4667 FT/SEC = 0.8690 KNOTS = 1.6093 KM/HR = 0.447041 M/SEC
 1 KNOT = 1 NAUTICAL MI (INTERNATIONAL)/HR = 1.1508 ST MI/HR = 1.6878 FT/SEC

ANGULAR VELOCITY [T⁻¹]

1 RAD/SEC = 0.1592 REV/SEC = 9.549 RPM = 57.296 DEG/SEC
 1 RPM = 0.01667 REV/SEC = 0.10472 RAD/SEC = 6 DEG/SEC

ACCELERATION [LT⁻²]

1 FT/SEC² = 30.4801 CM/SEC² = 0.6818 MI/HR-SEC

ANGLE

1 RADIAN = 360°/2 π = 57.29578 DEGREES = 10³ ANGULAR MILS
 1 DEGREE = 60 MIN = 0.01745 RADIAN
 1 MIN = 60 SEC = 2.90888 $\times 10^{-4}$ RADIAN
 1 MILITARY MIL = 360/6400 DEGREES = 0.05625 DEGREES
 1 SEC SLOPE = 4.848 MICRO IN/IN = 0.001 IN/17.19 FT
 1 SOLID ANGLE = 4 π STERADIANS = 12.566 STERADIANS = 1 SPHERE
 1 STERADIAN = 0.079580 SOLID ANGLE

MASS [M]

1 GRAM (G) = 2.20462 $\times 10^{-3}$ LB (AV) = 0.03527 OZ(AV) = 15.4324 GRAINS
 1 LB(AV) = 16 OZ(AV) = 7000 GRAINS = 256 DRAMS(AV) = 453.5924 G
 1 OZ(AV) = 16 DRAMS(AV) = 437.5 GRAINS = 28.34953 G
 1 SHORT TON = 2000 LB(AV) = 907.185 KG = 20 HUNDREDWEIGHT (SHORT)
 1 LONG TON = 2240 LB(AV) = 1016.0470 KG = 20 HUNDREDWEIGHT (LONG)

DENSITY [ML⁻³]

1 LB/FT³ = 5.787 $\times 10^{-4}$ LB/IN³ = 16.018 KG/M³ = 1.6018 $\times 10^{-2}$ G/CM³
 1 G/CM³ = 0.03613 LB/IN³ = 64.23 LB/FT³

PRESSURE [ML⁻¹T⁻²]

1 ATMOSPHERE (ATM) = 1.0133 BARS = 14.696 LB/IN² = 1.013246 $\times 10^6$ DYNE/CM² = 760 TORR
 = 1033.2 G/CM² (0°C) = 760 MM Hg (0°C) = 29.921 IN Hg (0°C)
 = 33.903 FT WATER (0°C)
 1 DYNE/CM² = 1.01971 $\times 10^{-3}$ G/CM² = 1.4504 $\times 10^{-5}$ LB/IN²
 1 BAR = 1.0 $\times 10^6$ DYNES/CM² = 0.98692(ATM)
 1 LB WT/IN² = 70.307 G/CM² = 68,947 DYNES/CM²

TEMPERATURE

TEMPERATURE DIFFERENCES: $\Delta 1^\circ$ CENTIGRADE (C) = $\Delta 1.8^\circ$ FAHRENHEIT (F)
 = $\Delta 1.8^\circ$ RANKINE (R) = $\Delta 1^\circ$ KELVIN (K) = $\Delta 0.8^\circ$ RE'AUMUR (R°)
 0°C = 273°K = 32°F = 492°R = 0°R°
 100°C = 373°K = 212°F = 672°R = 125°R°
 0°K = -273.16°C = -459.72°F

FORCE [MLT⁻²]

1 NEWTON = 1 $\times 10^5$ DYNES = 0.22481 LB WT
 1 DYNE = 2.2481 $\times 10^{-6}$ POUND WEIGHT = 7.2330 $\times 10^{-5}$ POUNDAL = 0.0010197G WT
 1 G WT = 0.07932 POUNDAL = 980.665 DYNES = 2.2046 $\times 10^{-3}$ LB WT
 1 LB WT = 32.174 POUNDALS = 453.59 G WT = 4.4482 NEWTONS
 1 POUNDAL = 0.031081 LB WT = 14.098 G WT = 1.3825 $\times 10^4$ DYNES

WORK & ENERGY [ML²T⁻²]

1 ABSOLUTE (ABS) JOULE = 1 NEWTON METER = 1 $\times 10^7$ ERGS = 1 $\times 10^7$ DYNE CM
 = 1 WATT SEC = 1 VOLT COULOMB = 0.73756 FT LB
 = 2.3889 $\times 10^{-4}$ KG CALORIE(MEAN) = 9.4805 $\times 10^{-4}$ BTU (MEAN)
 = 23.730 FT POUNDAL = 2.778 $\times 10^{-7}$ KW HR = 3.725 $\times 10^{-7}$ HP HR
 1 G CALORIE (MEAN) = 4.186 JOULE (ABS)
 1 G CALORIE (15°C) = 4.1855 JOULE (ABS) = 0.003968 BTU
 1 JOULE (INTERNATIONAL) = 1.000165 JOULE (ABS)
 1 KW HR = 3413.0 BTU (MEAN) = 2.6552 $\times 10^6$ FT LB = 1.3410 HP HR
 1 LITER ATM (NORMAL) = 3.7745 $\times 10^{-5}$ HP HR = 24.206 G CAL (MEAN)
 = 101.328 JOULES (ABS)
 1 ATOMIC MASS UNIT (AMU) = 931.16 MeV
 = 1.65983 $\times 10^{-24}$ G MASS (ENERGY EQUIV)
 1 ELECTRON VOLT (eV) = 1.60207 $\times 10^{-19}$ JOULE (ABS)

POWER [ML²T⁻³]

1 BTU (MEAN)/MIN = 0.023575 HP = 17.580 WATTS (ABSOLUTE) = 778.0 FT LB/MIN
 1 ERG/SEC = 10^{-10} KW = 1.3412 $\times 10^{-10}$ HP = 1 $\times 10^{-7}$ WATT
 = 5.688 $\times 10^{-9}$ BTU (MEAN)/MIN = 1.4333 $\times 10^{-9}$ KG CAL (MEAN)/MIN
 = 7.3756 $\times 10^{-8}$ FT-LB/SEC
 1 HP (MECH) = 0.70696 BTU (MEAN)/SEC = 550 FT LB/SEC = 745.70 WATTS
 = 10.688 KG-CAL/(MEAN)/MIN
 1 HP (ELECTRICAL) = 746.00 WATTS

TORQUE [ML²T⁻²]

1 DYNE-CM = 1.0197 $\times 10^{-8}$ KG-M = 7.3757 $\times 10^{-8}$ LB WT-FT
 = 8.8511 $\times 10^{-7}$ LB WT-IN = 2.3731 $\times 10^{-6}$ POUNDAL-FT
 1 KG-M = 9.8066 $\times 10^7$ DYNE-CM
 1 LB WT-FT = 1.3558 $\times 10^7$ DYNE-CM
 1 POUNDAL FT = 4.2140 $\times 10^5$ DYNE-CM
 1 LB WT-IN = 1.1298 $\times 10^6$ DYNE-CM

PHYSICAL CONSTANTS

h = PLANCK CONSTANT = (6.6252 $\pm$ 0.0005) $\times 10^{-27}$ ERG-SEC
 R₀ = GAS CONSTANT PER MOLE
 = (8.31662 $\pm$ 0.00038) $\times 10^7$ ERG/°K-MOLE (PHYSICAL SCALE)
 = (8.20545 $\pm$ 0.00037) $\times 10^{-2}$ LITER ATM/°K-MOLE (CHEM SCALE)
 k = BOLTZMANN CONSTANT = (1.38042 $\pm$ 0.00010) $\times 10^{-16}$ ERG/°K
 σ = STEFAN-BOLTZMANN CONSTANT (FOR BLACK BODY)
 = (5.6686 $\pm$ 0.0005) $\times 10^{-3}$ ERG/CM²-SEC-(°K)⁴
 c = VELOCITY OF LIGHT = (2.99793 $\pm$ 0.00001) $\times 10^{10}$ CM/SEC = 186,284 MI/SEC
 F = FARADAY CONSTANT = (96,520 $\pm$ 3) ABS COULOMBS/G EQUIVALENT
 e = ELECTRONIC CHARGE = (1.60207 $\pm$ 0.00007) $\times 10^{-19}$ ABS COULOMBS
 = (4.80288 $\pm$ 0.00021) $\times 10^{-10}$ esu
 e/m = SPECIFIC ELECTRONIC CHARGE = (1.75888 $\pm$ 0.00005) $\times 10^{11}$ ABS COULOMBS/KG
 N₀ = AVOGADRO'S NUMBER
 = (6.02472 $\pm$ 0.00036) $\times 10^{23}$ MOLECULES/G-MOLE (PHYSICAL SCALE)
 = (6.02308 $\pm$ 0.00040) $\times 10^{23}$ MOLECULES/G-MOLE (CHEMICAL SCALE)
 a_0 = $h^2/4\pi me^2$ = FIRST BOHR RADIUS = (5.29171 $\pm$ 0.00006) $\times 10^{-9}$ CM
 ϵ_0 = $1/\mu_0 c^2$ = PERMITTIVITY OF FREE SPACE = (8.8542 $\pm$ 0.0001) $\times 10^{-12}$ FARAD/M
 μ_0 = PERMEABILITY OF FREE SPACE = 4 π $\times 10^{-7}$ HENRY/M = 12.5664 $\times 10^{-7}$ HENRY/M

$Z_0 = (\mu_0/\epsilon_0)^{1/2}$ = IMPEDANCE OF FREE SPACE = (376.731 ± 0.001) OHM
 G = NEWTON'S GRAV CONSTANT = $(6.670 \pm 0.005) \times 10^{-8}$ CM³/G-SEC
 g = ACCELERATION DUE TO GRAVITY (STANDARD) = 32.174 FT/SEC²
 $= 980.665$ CM/SEC² = 386.09 IN/SEC² = 21.94 MI/HR-SEC
 REST ENERGY OF THE ELECTRON = 0.51098 MeV
 ELECTRON MASS = $(9.1085 \pm 0.0006) \times 10^{-28}$ G = 0.51098 MeV = 5.48760×10^{-4} AMU
 PROTON MASS = $(1.67243 \pm 0.00010) \times 10^{-24}$ G = 938.232 MeV = 1.007593 AMU
 NEUTRON MASS = $(1.67474 \pm 0.00010) \times 10^{-24}$ G = 939.526 MeV = 1.008982 AMU
 α PARTICLE MASS = $(6.6442 \pm 0.0012) \times 10^{-24}$ G = 3727.377 MeV = 4.00294 AMU
 H^1 ATOM MASS = $(1.67335 \pm 0.00010) \times 10^{-24}$ G = 938.743 MeV = 1.008142 AMU

MISCELLANEOUS CONSTANTS & CONVERSIONS

DENSITY OF WATER AT 3.98°C , 760 MM HG = 0.3613 LB/IN³ = 62.43 LB/FT³
 $= 1$ G/ML = 0.999973 G/CM³
 DENSITY OF AIR (STP) = 1.293×10^{-3} G/CM³
 STP = STANDARD TEMPERATURE & PRESSURE = 0°C & 760 MM HG
 WATER HEAT OF FUSION (0°C) = 79.71 G-CAL (15°C)/G
 WATER HEAT OF VAPORIZATION (100°C) = 539.55 G-CAL (15°C)/G
 MOLAR VOLUME (STP) = 359 FT³/LB-MOLE
 $= (22.4207 \pm 0.0006)$ LITERS/G-MOLE (PHYSICAL SCALE)

VELOCITY OF SOUND: IN AIR (STP) = 331.7 M/SEC = 1088 FT/SEC
 IN WATER (20°C) = 1470 M/SEC = 4823 FT/SEC
 ATTENUATION OF SOUND IN AIR (STP-37%RH) = $\approx 6 \times 10^{-14}$ dB (KC)²/FT
 VISCOSITY OF WATER (20°C) = 1.002 CENTIPOISE = 0.01002 DYNE-SEC/CM²
 1 CURIE ACTIVITY = 3.7×10^{10} DISINTEGRATIONS/SEC = 3.7×10^4 RUTHERFORD
 1 ROENTGEN (r) RADIATION DAMAGE = IONIZATION BY X- OR GAMMA-RAYS PRODUCING 1 esu OF CHARGE IN 1 CM³ AIR (STP)
 1 BARN CROSS SECTION = 10^{-24} CM²
 RATIO PHYSICAL (0^{16} = 16) TO CHEMICAL SCALE (0 = 16) OF ATOMIC WEIGHTS
 $= 1.000272 \pm 0.000005$
 M = MASS OF EARTH = 5.983×10^{24} KG = 6.595×10^{21} TONS
 INTERFERENCE FRINGE = 11.6 MICROINCHES/FRINGE (He LINE = $5875.6\text{\AA}$)
 $\pi = 3.1415926535 +$
 $e = 2.7182818284 +$
 $\text{LOG}_{10} N = \text{LOG}_{10} 10 \times \text{LOG}_{10} N = 2.3026 \text{ LOG}_{10} N$
 1 KW HR $\approx 4.2 \times 10^{-5}$ G U²³⁵ IN FISSION
 $\approx 6.4 \times 10^{-6}$ G H³ IN H³ (d,n)He⁴ REACTION
 $\approx$ AVERAGE NOON INSOLATION IN 1 HOUR ON HORIZONTAL PLANE OF 1 M²
 ≈ 0.74 LB (HIGHEST POWER STATION EFFICIENCY ON 12,500 BTU/LB COAL)

SOURCE: GENERAL ELECTRIC OPTICAL ENGINEERING HANDBOOK 1962.

Density-% Transmission(OPACITY $\times$ %TRANSMISSION = 100)

Density	Opacity	Trans- mission %	Density	Opacity	Trans- mission %	Density	Opacity	Trans- mission %
0	1.0	100.						
0.1	1.3	80.	1.1	13.	8.0	2.1	130	0.80
0.2	1.6	63.	1.2	16.	6.3	2.2	160	0.63
0.3	2.0	50.	1.3	20.	5.0	2.3	200	0.50
0.4	2.5	40.	1.4	25.	4.0	2.4	250	0.40
0.5	3.2	32.	1.5	32.	3.2	2.5	320	0.32
0.6	4.0	25.	1.6	40.	2.5	2.6	400	0.25
0.7	5.0	20.	1.7	50.	2.0	2.7	500	0.20
0.8	6.3	16.	1.8	63.	1.6	2.8	630	0.16
0.9	8.0	13.	1.9	80.	1.3	2.9	800	0.13
1.0	10.0	10.	2.0	100.	1.0	3.0	1000	0.10

Photometric Units

1 Footcandle	=	1 Lumen/FT ²
1 Footcandle	=	10.764 Meter Candles
1 Candle	=	1 Lumen/Steradian
1 Candle/M ²	=	3.142×10^{-4} Lambert
1 Lambert	=	2.054 Candle/In ²
1 Lux	=	1 Meter Candle
1 Lux	=	0.0929 Footcandle
1 Meter Candle	=	1 Lumen/M ²

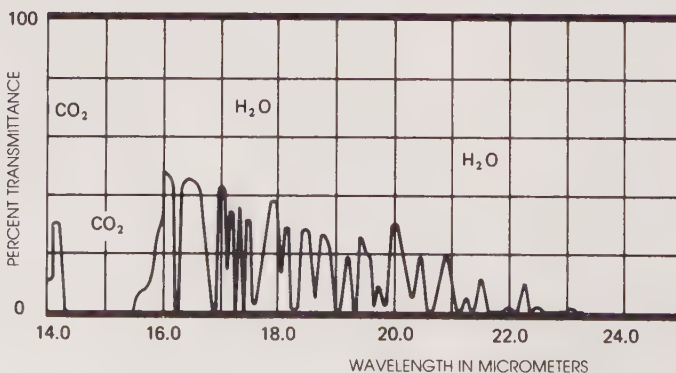
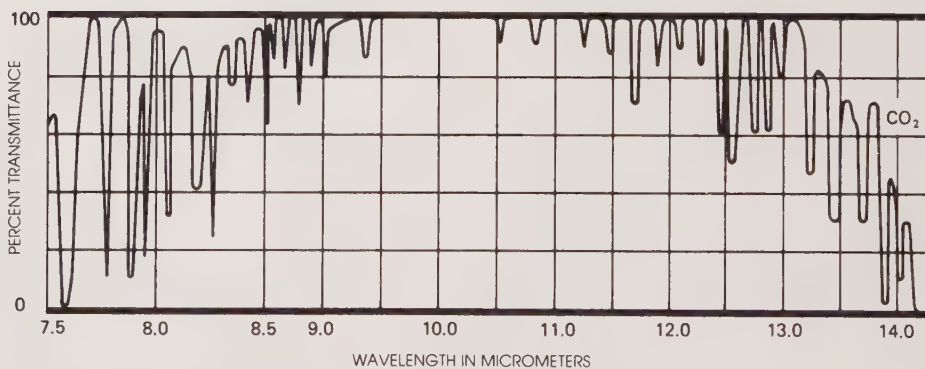
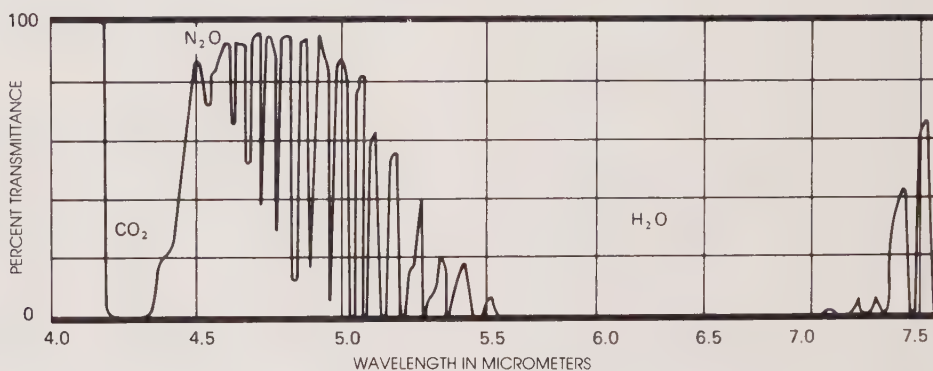
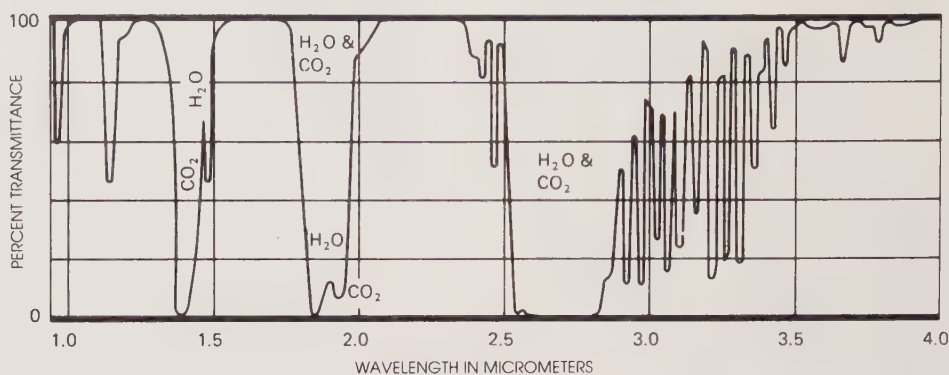
NOTE: 1 Lumen = average light emission
 of one candle into unit solid angle
 (in Steradians).
 1 Lumen = 0.001496 watt of mono-
 chromatic light at 546nm.

Angle Conversions

	Degree	Min	Sec	Rad	mrad	Circumference	Quadrant
1 Degree (°)	= 1	60	3600	1.7453×10^{-2}	1.7453×10^{-5}	2.7778×10^{-3}	1.11112×10^{-2}
1 Minute (')	= 1.66667×10^{-2}	1	60	2.9089×10^{-4}	2.9089×10^{-7}	4.6296×10^{-5}	1.8518×10^{-4}
1 Second (")	= 2.77778×10^{-4}	1.66667×10^{-2}	1	4.8481×10^{-6}	4.8481×10^{-9}	7.71605×10^{-6}	3.0864×10^{-5}
1 Radian (rad)	= 5.72958×10^1	3.43775×10^3	2.06265×10^5	1	10^3	1.59155×10^{-1}	6.3662×10^{-1}
1 Milliradian (mrad)	= 5.72958×10^{-2}	3.43775	2.06265×10^2	10^{-3}	1	1.59155×10^{-4}	6.3662×10^{-4}
1 Circumference	= 360	21,600	1,296,000	6.28319	6.28319×10^3	1	4
1 Quadrant	= 90	5400	324,000	1.5708	1.5708×10^3	0.25000	1

Spectral Location of Atmospheric Absorption Bands

For a 1000-ft. horizontal air path at sea level with 5.7mm precipitable water at 26°C temperature, within the wavelength interval from 1μ to 25μ .



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Analytical Instruments

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Calibrating a Picosecond Streak Camera

In combination with a picosecond mode-locked laser, a streak camera can temporally resolve high-speed events. This capability has helped open up new fields of research for physicists, biologists and chemists studying the intricacies of the molecular world. Most of the basic processes occur on a picosecond time scale, so the development of streak camera technology is intimately related to the progress of picosecond and sub-picosecond laser techniques. Table 1 lists the typical pulse durations achieved to date.

General operation

A streak camera spectroscopic system consists of a streak tube (Fig. 1), imaging optics, fast sweeping electrodes and video display/computer equipment. Light incident onto the photocathode produces an emission of electrons proportional to the light intensity. These electrons are accelerated by a high-voltage mesh into the streak tube, and are electrostatically swept at a known rate over a known distance, thus converting temporal information into spatial information. Electrons emitted at different times are deflected to different positions on a microchannel plate that produces electron multiplication through secondary emission. These secondary electrons impinge upon a phosphor screen, forming a streak image that is viewed by a filmback or by an electronic video readout system.

Dynamic range

The dynamic range of a streak camera is commonly defined as the input intensity at which the streak camera output pulse width is broadened by no more than 20%, using the pulse duration of lower intensity pulses (t_0) as a reference.¹ The ratio of the highest to the lowest incident light intensity for which this condition is satisfied is the linear dynamic range. Often, the video readout system limits the dynamic range by saturating before the camera, and thus a proper video recorder choice must be made to be able to utilize the full dynamic range of the camera. Typical dynamic range of streak cameras not limited by a readout system is 1000:1. Factors which limit the dynamic range are microleasing effects and space charge saturation near the photocathode. These effects

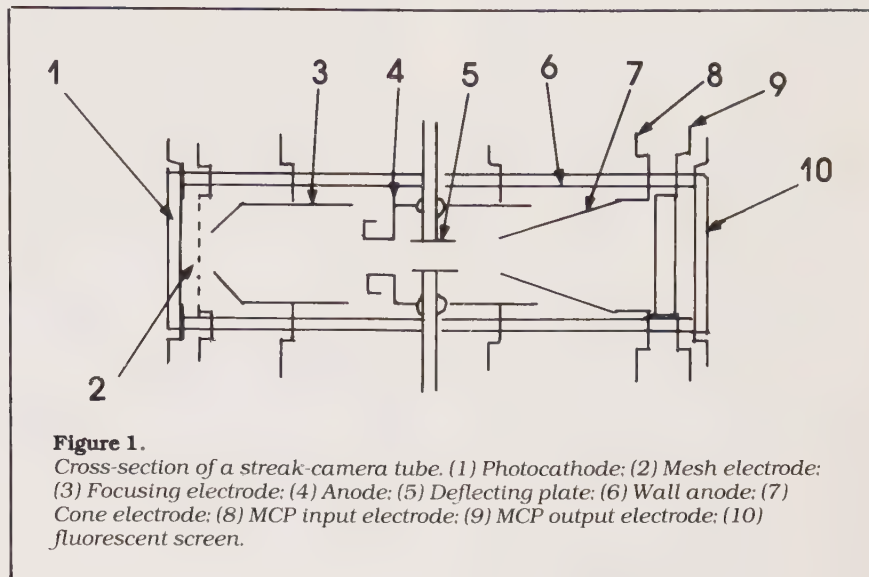


Figure 1.

Cross-section of a streak-camera tube. (1) Photocathode; (2) Mesh electrode; (3) Focusing electrode; (4) Anode; (5) Deflecting plate; (6) Wall anode; (7) Cone electrode; (8) MCP input electrode; (9) MCP output electrode; (10) fluorescent screen.

cause temporal broadening of the focused beam when the current density inside the tube is large.

Calibration in time and intensity

All streak cameras at present require time and intensity axis calibration in order to display a kinetic intensity profile versus time of an event, as measured with a camera-video system. We describe such a calibration technique below.

Calibrating the time axis and linearity of a camera system in the streak mode requires an optical single pulse that has a duration (FWHM) that is less than the resolution of the camera and a wavelength within the spectral response of the unit. For this technique we use a single pulse

extracted from the output train of a mode-locked laser. The pulse passes through a pair of mirrors (etalon) of transmission coefficient T coated for the wavelength of the pulse employed. Typically a transmission coefficient of 10 percent will yield the best results. The laser's pulse duration in space is much less than the etalon spacing.

Figure 2 shows a schematic diagram of the calibration system.² By passing the pulse through an etalon of known time spacing (d), a series of exponentially decaying intensity pulses will emerge. The calibrating pulses produced in this manner are a train separated in time ($\Delta t = 2d/c$, where c is the velocity of light). The intensity profile of the emerging train is a decaying exponential with each subse-

TABLE 1.
MODE-LOCKED LASERS

Laser	Wavelength (nm)	Mode-Locking Dye	Typical Laser Pulse Duration (psec)
Ruby	694.5	DDI in (methanol)	10-30
Nd:YAG	1064	9860, 9740 in (dichloroethane)	30
Nd:glass (silicate)	1060	9860 in (dichloroethane)	8-10
Nd:glass (phosphate)	1054	9860 in (dichloroethane)	6-7
		5 in (dichloroethane)	3-4
Rh6G	570-610	Synch pump	2-6
Rh6G	610	DODCI	0.5-0.03

quent peak reduced by $(1-T)^2$. For each round trip of the pulse between the mirrors, a light pulse (K) of intensity $I_K = I_0 (1-T)^{2K}$ is produced, where $K = 0, 1, 2, \dots, n$. Since I_K/I_{K+1} equals $1/(1-T)^2$ equals constant, the envelope formed by the peaks of the pulses follows a single exponential decay in time as $I = I_0 \exp(-t/\Delta t \ln(1-T)^2)$, where the time between peaks is $t + K \Delta t$. The peaks are used to calibrate the time axis.

This technique, with appropriate etalon transmission, may also be used to measure transient dynamic range, but is typically too noisy and may disguise the minimum measurable signal, thereby limiting the dynamic range measurements. The sweep rate per channel $\Delta t/\Delta X$ versus the average channel number (X) is used to calibrate the time base and intensity variations of the camera where X is the number of channels between peaks and Δt is fixed for a given etalon mirror spacing.

Using this calibration technique, we can generate curves representing sweep rate ($X = At$) and sweep speed linearity. The streak speed in picoseconds/channel for each scale can be determined from their sweep rate curve.

The intensity spatial profile as a function of distance ($I(x)$) along the phosphor screen is usually measured

with a video system. In order to obtain the intensity as a function of time ($I(t)$) from that profile, one must take into account the streak rate for each channel. This rate is nonlinear, and it is intuitively clear that the $I(x)$ the video system measures is not the true $I(t)$.

For example, let us assume that the rate at one channel is larger than at a later channel; that is, the voltage ramp is such that the deflected electron beam excites the phosphor at the first channel longer than at the second channel to which it is deflected later in time. Furthermore, let us assume that the intensity of light is equal at both times. Clearly, while in reality the intensities are equal, the video system will read more intensity at the first channel because it collected the deflected electrons longer. Therefore, it is obvious that when the streak rate is nonlinear, one must take into account the differing rates to get the true $I(t)$ from $I(x)$.

The streak rate is taken into account by setting $I(t)dt = I(x)dx$, or:

$$I(t) = I(x) \frac{dx}{dt}$$

This means that I at a certain point on the x axis is multiplied by an infinitesimal amount dx and that this must be equal to I at the corre-

sponding point on the t axis times an infinitesimal amount dt . Since $I(x)dx$ is the total intensity measured in the immediate vicinity of x , and $I(t)dt$ is the total intensity measured in the immediate vicinity of t , this simply requires that the total intensity measured at x equal the total intensity measured for the corresponding time. The equation above tells us that by multiplying the $I(x)$, measured at each channel by the video system, by the $\Delta x/\Delta t$ of that channel, x , we can obtain the intensity as a function of time.

Now that $I(t)$ has been obtained one has to convert the x axis into a time axis. This is done by noting:

$$t = \frac{dt}{dx} dx$$

In effect, this is doing the integral

$$t = \int (dt/dx) dx$$

numerically, which is necessitated by the fact that we have values at discrete channels and do not have a continuous curve. Because of the nonlinear streak rate, the distance between equal times will vary. However, since we now know the time to which each point on the x axis corresponds, and we know the value of $I(t)$ at that point, it is easy to regraph the ordered pairs ($t, I(t)$) so distance between equal times is equal.

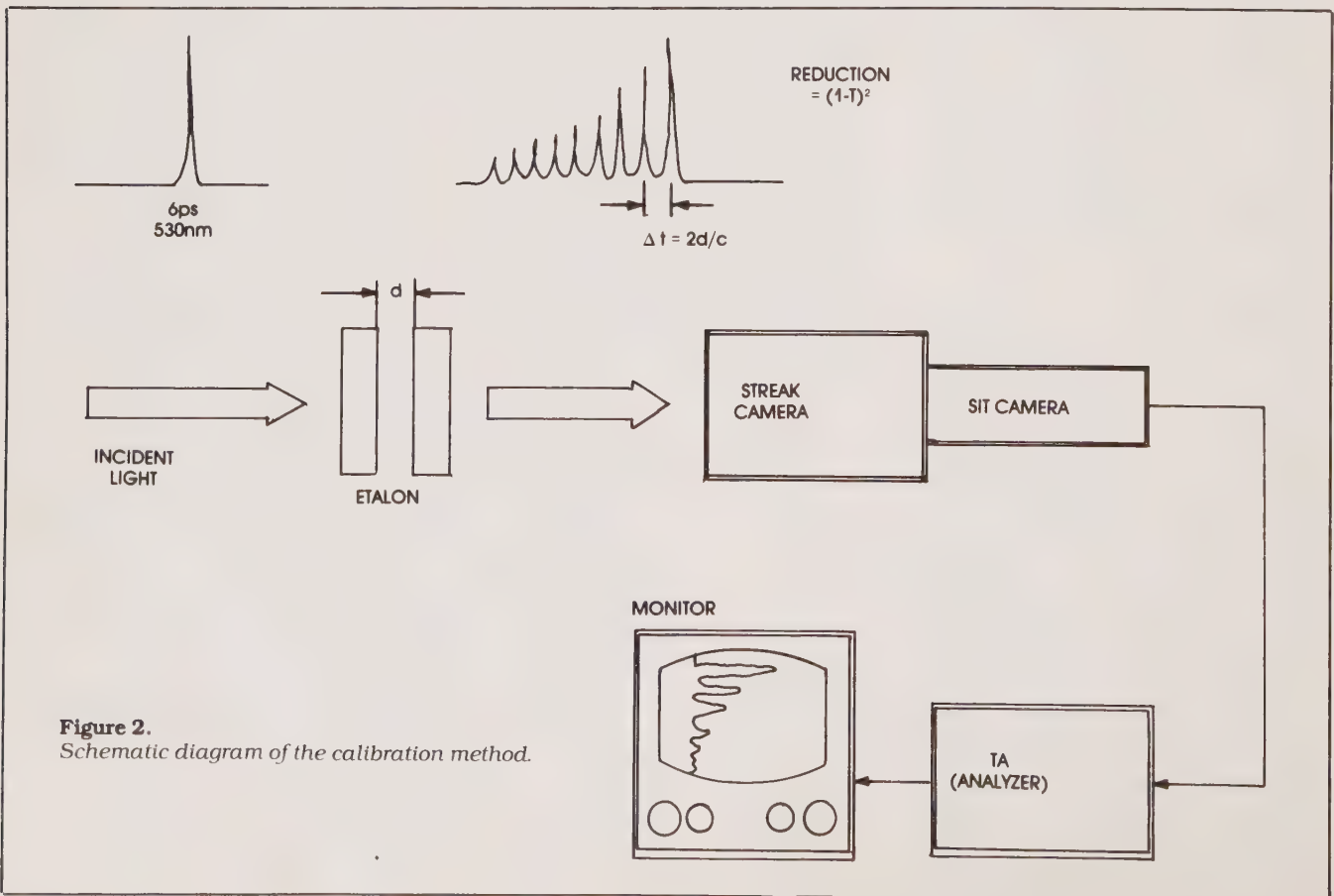


Figure 2.
Schematic diagram of the calibration method.

Streak cameras exhibit trigger jitter and trigger delay. Trigger jitter is the difference, from shot to shot, in the time between the arrival of the trigger signal and the beginning of the actual deflection sweep. Typically, jitter ranges from a psec to tens of nsec, depending on the streak camera model, manufacturer and trigger circuitry scheme. Jitter and fluctuations in sweep speed are two problems that constantly haunt the streak camera user.

In order to reduce the fluctuations in sweep and jitter, some systems employ a light-activated silicon switch.³ These switches, which are silicon transmission lines that exhibit quasi-metallic photoconductivity when excited by intense-light picosecond pulses, have the advantage that their intrinsic switching speeds are limited primarily by the exciting optical pulse width. When used to directly trigger a streak camera, a high-voltage bias is applied to the switch, which, when

opened upon excitation by that part of the laser beam sent to it, provides the deflection voltage for the streak camera. The silicon switch's pulse-width-limited risetime results in a relatively stable streak speed and nearly negligible jitter (1.7psec).

In most commercial systems, the deflecting voltage is triggered by a low-voltage pulse produced outside the streak camera. In order to synchronize the arrival of the light signal with the beginning of the deflection sweep, a portion of the laser pulse is split off to a pin diode to produce the trigger pulse. The pulse to be investigated is sent along a delay path so that it arrives at the camera when streaking begins. Trigger delay is the amount of elapsed time between the production of a trigger signal and the beginning of the deflection sweep. Streaking begins 10 to 100nsec after triggering, depending on the sweep rate, and the trigger delay time varies

for different sweep settings. Light takes approximately 3.3nsec to travel 1 meter in air. In addition to the optical delay path, an electronic delay is necessary as a means of making incremental changes in the delay time. This fine tuning is necessary to compensate for jitter, as well as to provide the change in delay time needed when changing streak speeds.

Table 2 lists some of the commercially available picosecond streak cameras with various characteristics.

H.R. Dorsinville, R.R. Alfano
and N.H. Schiller

References

1. Thomas, S. W., and R.L. Peterson (1982). International Congress on High Speed Photography and Photonics, San Diego, CA, August 21-27, 1982.
2. Tsuchiya, Y. and E. Inuzuka (1979). *Proc. National Convention of Inst. Engineers of Japan*, 407-408.
3. Knox, W. and G. Mourou (1981). *OPT. COMM.* 37,203.

Table 2.
Comparison of Picosecond Streak Cameras

MANUFACTURER*	HAMAMATSU		HADLAND		CORDIN	THOMPSON
MODEL	C979	C1370	675/II (with 50/40)	675/II (with 50/40)	179-LLL	TSN 504-04
Time Base Configuration	Fast Plug-In	Ultrafast	Standard Variable 44 steps	Ultrafast Plug-In	Individual Plug-Ins	Plug-In
Sweep Range Full Scale	Variable 1, 2, 5, 10nsec	Variable 0.38, 0.5, 1.2nsec	1.5 to 500nsec	Fixed 0.5nsec	Fixed 1.3, 4, 13nsec	Variable 1, 2, 5, 10, 20nsec
Maximum Time Resolution for S-20 Photocathode at 530nm	10psec	2psec	4psec	2psec	10psec	5psec
Maximum Streak Velocity	67psec/mm	25psec/mm	30psec/mm	10psec/mm	33psec/mm	25psec/mm
Streak Image Output Format	15mm Dia.	15mm Dia.	15 x 50mm	15 x 50mm	40 mm Dia.	25 x 40mm
Time Window (at Maximum Streak Velocity)	1nsec	375psec	1.5nsec	500psec	1.3nsec	1nsec
Electronic Trigger	Minimum Delay 11nsec	11nsec	12nsec	30nsec	16nsec	15nsec
Characteristics	Jitter ±50psec	±50psec	±25psec	±500psec	±100psec	≤300psec
Electrical Pulse Voltage	2-10V (50 ohm)	2-10V (50 ohm)	10V (50 ohm)	10V (50 ohm)	30-50V (50 ohm)	50V (50 ohm)
Direct Optical Input Trigger	Minimum Delay —	—	1.5nsec	—	1.7nsec	—
Characteristics	Jitter —	—	±25psec	—	>100psec	—
Optical Pulse Energy	—	—	10μJ	—	1-10μJ	—
Spatial Resolution	7 lp/mm	25 lp/mm	7 lp/mm	7 lp/mm	7 lp/mm	12 lp/mm
Photocathode Format	4.2mm Dia.	9mm Dia.	7.5mm Dia.	7.5mm Dia.	13mm Dia.	35mm Dia.
Photocathode	S-1, S-20 Multialkali (UV glass)	S-20 Multialkali (UV glass)	S-1 S-20 S-20UV	S-1 S-20 S-20UV	S-1 S-20	S-20 S-20UV
Image Intensifier**	Built In	Built In	External	External	External	Built In

* Each manufacturer makes a variety of different model streak cameras, plug-ins and accessories. For the sake of brevity, each manufacturer is represented by no more than two units. The parameters displayed in the table were obtained from information supplied by the manufacturers or compiled from available datasheets. Since there are no standard definitions used to define the various parameters, the authors are not responsible for, or knowledgeable of, the testing techniques used by the other manufacturers in obtaining the values used in this table. Equal numbers may not represent an equal comparison in all cases.

** For the Image Intensifier, "Built In" indicates that the intensifier is built into the streak tube.

Optical Encoders

There are two basic generic styles of optical encoders: incremental and absolute.

The incremental encoder creates a series of equally spaced signals corresponding to the mechanical increment required; i.e., to divide a shaft rotation into 1000 parts, an encoder could be selected to supply 1000 square-wave cycles per revolution. By using a counter to count those cycles, we could tell how far the shaft rotated. One hundred counts would

equal 36 degrees, 150 counts 54 degrees, etc. We are limited only by the counter's register capacity. The number of cycles per revolution is limited by physical line spacing and quality of light transmission.

An absolute encoder provides a "whole word" output with a unique code pattern representing each position. This code is derived from independent tracks on the encoder disk corresponding to individual photo-

tectors would then be high or low depending on the code-disk pattern for that particular position.

Absolute encoders are used in applications where a device is inactive for long periods of time or moves at slow rates, such as flood control, telescopes, cranes, etc.

Absolute encoders are capable of using many thousands of different codes but the most common are Gray, Natural Binary and Binary Coded Decimal (BCD).

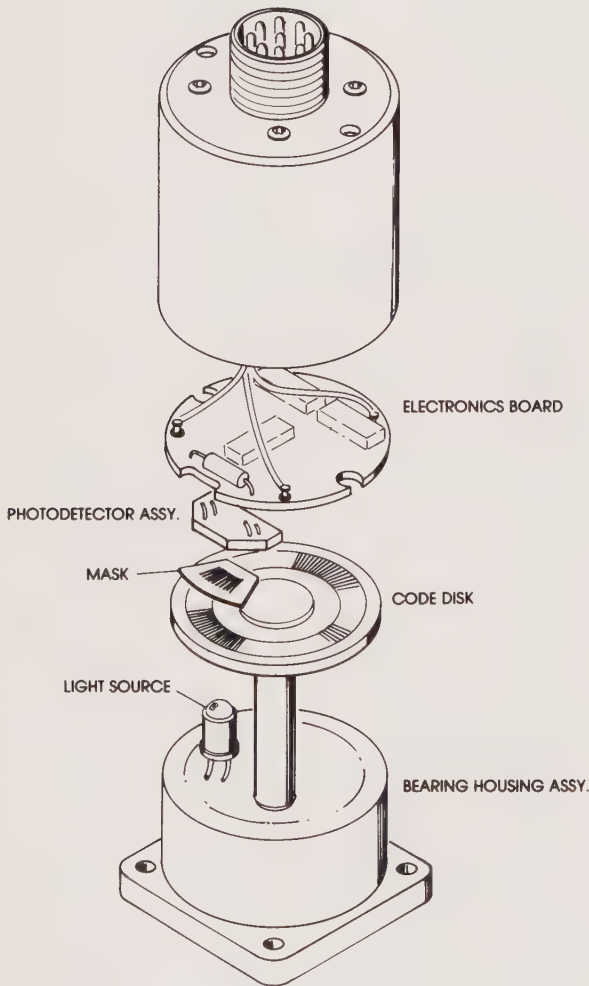


Figure 1.
Schematic of an incremental encoder.

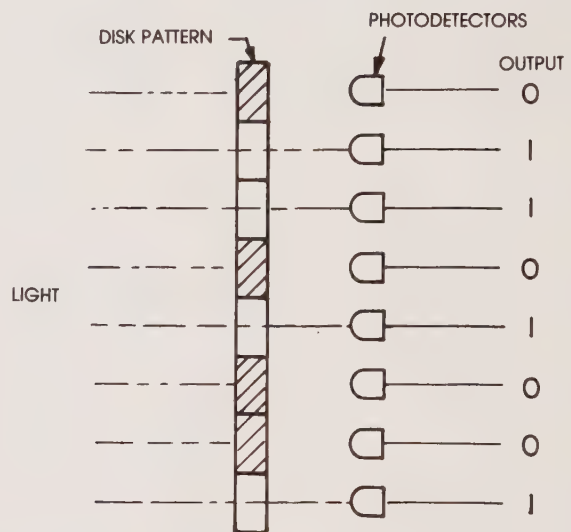


Figure 2.
An absolute encoder's output.



Figure 3.
Sample 8-bit encoder disk.

Types of Incremental Encoders

Tachometer encoder

A tachometer encoder is sometimes called a single-track incremental encoder because it has only one output and cannot detect direction. The output is in most cases a square wave.

Velocity information is available by looking at the time interval between pulses or at the number of pulses within a time period. When using the interval between pulses, the encoder should provide good edge-to-edge accuracy. Any inaccuracy will

cause the servo system to constantly correct "errors" caused by disk-pattern irregularities.

Quadrature encoder

Most incremental systems use two output channels in quadrature for position sensing. This allows us to count the transitions. Using this information we can determine if "A" leads "B," and thus derive direction.

It is important to have this directional information available due to the vibration inherent in almost any

system. An error in count will occur should the encoder using a single channel (tachometer type) stop on a transitional edge. As vibration forces the unit back and forth across this edge, the counter will up-count with each transition even though the system seems to be stopped. By utilizing quadrature detection on a two-channel encoder and viewing the transition in its relationship to the state of the opposite channel, we can thus generate reliable directional information.

Count Multiplication

Direction sensing: pulse multiplication

Once the quadrature signal is decoded we can generate pulses of fixed duration at selected edge transitions within a cycle. These pulses can be fed via clockwise and counterclockwise output lines to an up-

down counter or programmable controller input port (see waveform drawing). Many counter and P.C. manufacturers use a quadrature detection circuit in electronics. This allows a two-channel quadrature input without further conditioning.

With quadrature detection we

have the ability to derive $1 \times$, $2 \times$ or $4 \times$ the basic code disk resolution. Ten thousand pulses per turn can be generated from a 2500-cycle two-channel encoder. With a quality disk and a properly phased encoder, this $4 \times$ signal will be accurate to better than $\frac{1}{2}$ count.



Figure 4.
Tachometer encoder.

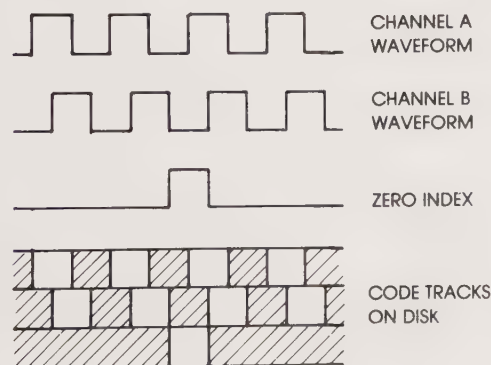


Figure 5.
Quadrature encoder.

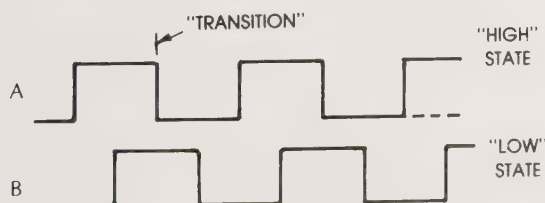


Figure 6.
A quadrature encoder's two output channels.

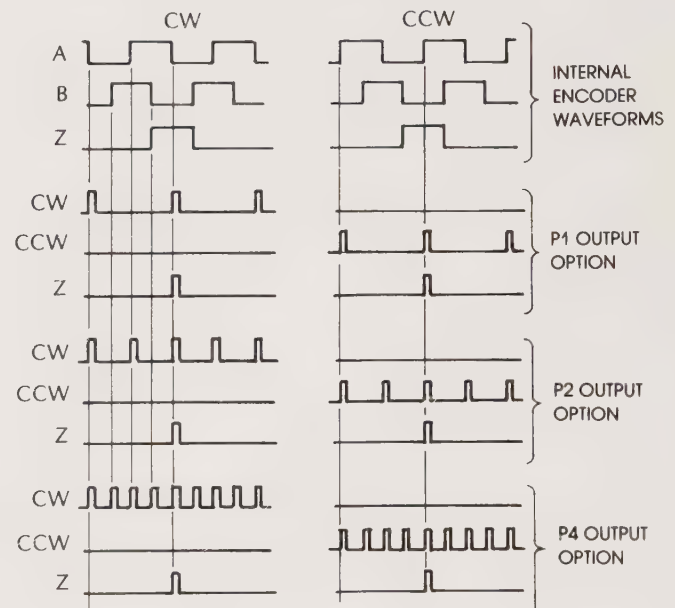
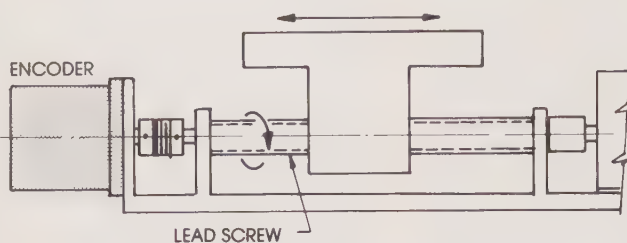


Figure 7.
Direction sensing (pulsed output).

Typical Application Examples

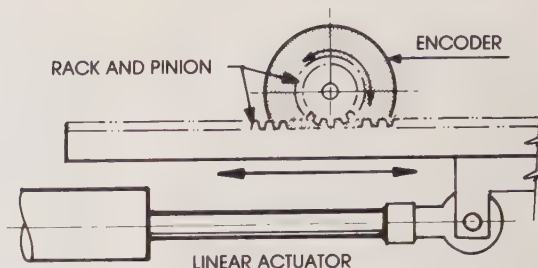
LATHE N/C DISPLAY



Purpose: To encode the lead screw
20 ft. cable length
500 RPM

Parameters: 1/4 pitch
20" travel
0.0005 resolution
Oil mist
To integrate with 6 decade
quadrature counter
5V power supply

LINEAR ACTUATOR



Purpose: To encode rack and pinion

Parameters: 40 tooth 1/20 pitch (1/2 turn/inch)
100 RPM max
20" stroke
0.0002 resolution
Clean environment
18" cable length
To integrate with 6 decade pulse counter
(requires CW, CCW input)
5V power supply
Flat on shaft for pinion

Source: BEI Industrial Encoder Division, Motor Systems Company

Credibility.

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Coating & Vacuum Science

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Optical Coatings for UV/VUV

The increasing use of short-wavelength excimer and UV lasers — for such applications as semiconductor processing, pumping of tunable dye lasers, isotope separation and enrichment, generation of extreme UV radiation, photochemistry and spectroscopy — has prompted the development of new types of optical coatings for the wavelength region below 360nm. It has also created new challenges for optical coating manufacturers, because material limitations are much more severe in the UV and vacuum UV (VUV) than in the visible wavelengths.

The design of short-wavelength coatings requires extensive materials research, computer-aided thin film design, and a practical knowledge of coating materials properties. Production of the coatings, too, calls for precisely controlled deposition and monitoring equipment as well as measurement equipment for quality control. But putting all these elements together has produced several high-efficiency optical coatings designed for use with short-wavelength radiation.

Enter the multilayer dielectrics

The first high-reflectance UV and VUV coatings, developed in the late 1950s, were of a design incorporating an aluminum-based layer with magnesium fluoride enhancement (Al/MgF_2). Coatings of this type are still widely used for applications that require high reflectance over a wide spectral region. In 1973 Acton Research developed a series of multilayer dielectric (MLD) coatings that offered better efficiency than the best Al/MgF_2 coatings, and varying the coating materials, the number of layers, and the thickness of the layers deposited onto a substrate resulted in many different types of coatings. Multilayer dielectric coatings designed for maximum reflectance, partial reflectance, and antireflectance are now produced on a commercial basis for wavelengths as short as 145nm.

As shown in Figures 1 and 2, typical MLD coatings for this region offer high efficiency over a narrow band centered at the laser wavelength. Figure 1 shows the reflectance characteristics of an MLD coating designed for maximum reflectance at 193nm (the ArF laser wavelength) at 45°. Figure 2 shows a similar MLD coat-

ing for 248nm (the KrF laser wavelength). Although only 55nm apart, the reflectors are constructed from different materials to maximize efficiency and minimize absorption.

Some of the new coatings developed for the wavelength region below 360nm include dual wavelength beam-turning and beamsplitting coatings, improved broadband UV

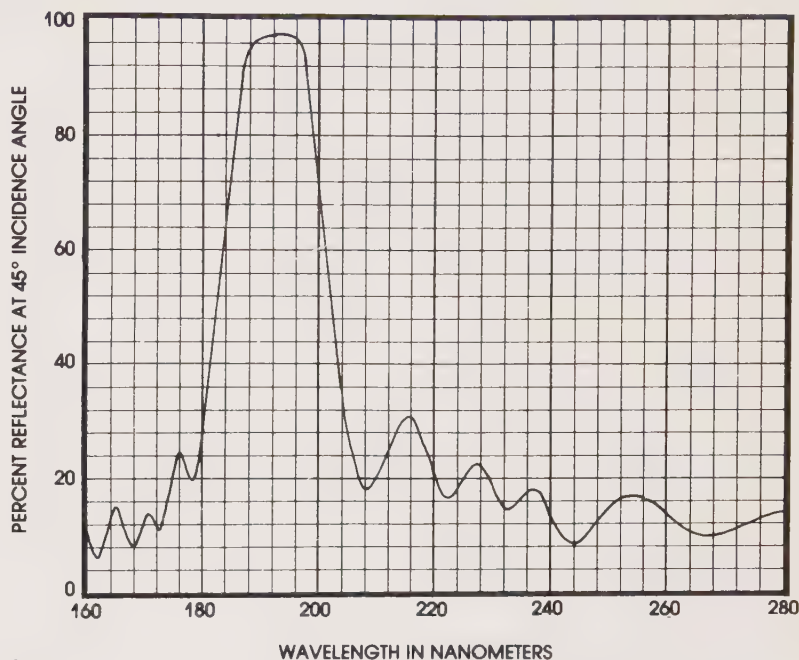


Figure 1.

Measured reflectance of a standard multilayer dielectric (MLD) beam-turning coating for use at 193nm (ArF laser wavelength) at 45° incidence angle.

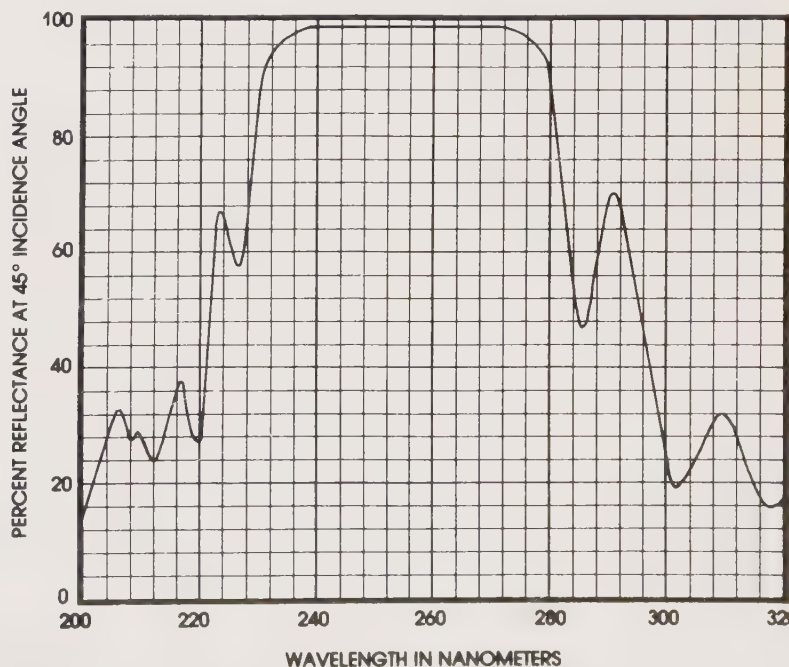


Figure 2.

Measured reflectance of a standard MLD beam-turning coating for use at 248nm (KrF laser wavelength) at 45° incidence angle.

reflective coatings, and soft x-ray multilayer coatings. Many of these, described below, were produced for specific applications but have become useful in other areas as well.

Dual-wavelength beam-turning coatings

Often it is necessary to keep a laser fixed in position while directing the

output beam to various experiments. This is normally accomplished with one or more mirrors that are highly reflective at the laser wavelength and at a specific incidence angle, such as 45° . As shown in Figures 1 and 2, standard beam-turning mirrors of the MLD design offer near-total reflectance at the laser wavelength at 45° , and thus

energy loss is kept to a minimum.

One common problem in directing an excimer or UV laser beam to an experiment is accurate alignment of the mirrors. Because the UV wavelengths can't be seen, the experimenter normally relies on a visible source, such as a helium-neon laser, to align the mirrors. Unfortunately, however, standard UV-optimized MLD coatings offer poor reflectivity away from the design wavelength and thus make it difficult to use a visible source for alignment purposes, especially when using several mirrors. While it is true that metallic-based coatings, such as enhanced aluminum, reflect well (85 to 92 percent) at both UV and visible wavelengths, they are normally limited to lower-power applications because of their high absorption.

To meet the requirements of high-power applications, it thus became necessary to develop an all-dielectric MLD coating that would offer performance similar to standard UV beam-turning mirrors while also reflecting visible wavelengths for alignment purposes. Several computer simulations and test coatings led to the conclusion that a suitable dual-wavelength beam-turning mirror could be produced.

Figure 3 shows the reflectance characteristics of a coating that offers maximum beam-turning qualities at 248nm with good reflectance at 633nm for alignment purposes. Minor alterations in coating design enable the dual-wavelength beam-turning mirrors to be produced for other wavelengths, and new materials now being researched promise further improvements for this type of reflector.

Dual-wavelength beamsplitting coatings

The development of MLD beam-splitting coatings that operate at 248nm and 633nm was motivated by the same alignment considerations as MLD beam-turning coatings. The dual-wavelength beam-splitting coatings of the MLD design are special coatings that manifest approximately 50 percent transmission at both wavelengths. They permit the efficient beamsplitting of 248nm (KrF) laser radiation and accurate alignment using a helium-neon laser emitting at 633nm.

Such beamsplitting coatings, however, are more difficult to design than standard ultraviolet MLD coatings, as they require materials and substrates that are compatible in both wavelength regions and with each other. In addition, each mirror

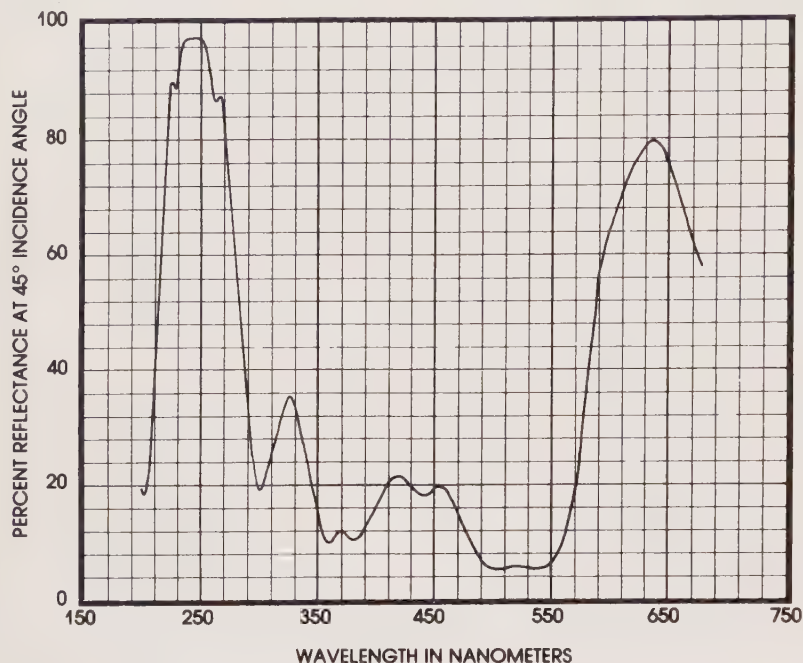


Figure 3. Dual-wavelength beam-turning coating designed for maximum reflectance at 248nm and 633nm at 45° incidence angle.

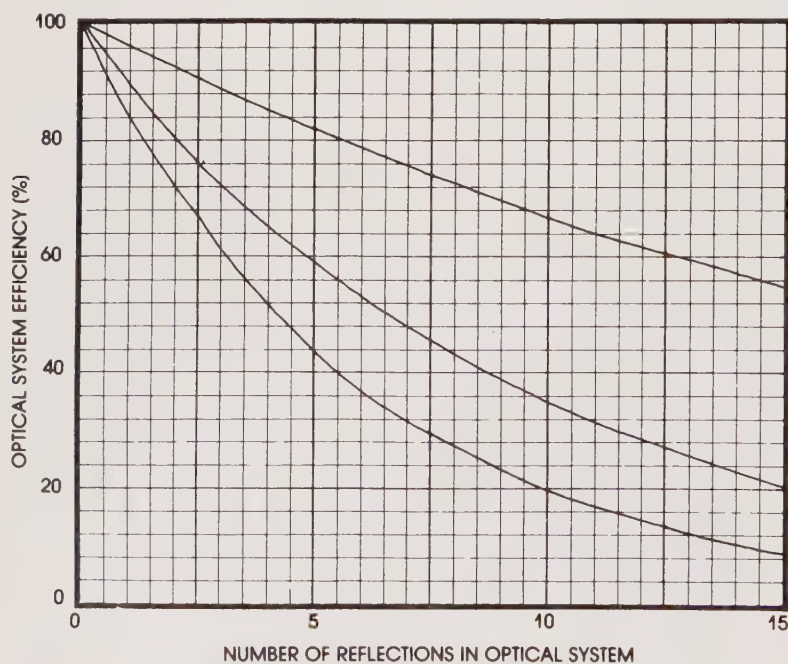


Figure 4. Effect of optical coating reflectance on optical system efficiency as a function of the number of reflections in the system. Upper curve represents 96 percent reflectance per mirror, middle curve 90 percent, and lower curve 85 percent.

must be measured for reflectance and transmission both at the design wavelengths and at the design angle to assure that the coatings meet specifications. A measurement of percent transmission alone is not sufficient, as this does not show the amount of absorption present and consequently could lead to improper performance or damage under high-power UV laser radiation.

The typical equipment for measuring reflectance and transmission at various incidence angles in the UV and VUV regions might consist of a UV-VUV light source (ARC #DS-775), a monochromator (ARC #VM-502), a reflectometer (ARC #VRSC-100) and a detection system (ARC #DA-781-VUV). Similar measurements for the UV and visible wavelengths are performed on a UV-VIS scanning spectrometer with a specular reflectance attachment.

The result of combining suitable materials with precisely controlled coating procedures and careful measurements is the production of dual-wavelength beamsplitters with high efficiency, low absorption and excellent power-handling capabilities. Outside testing has shown that dual wavelength beamsplitters have a damage threshold in excess of $2.0\text{J}/\text{cm}^2$ 20nsec pulse duration.

Superior broadband UV-reflective coatings

As I have said, one of the most common reflective coatings for the UV and vacuum UV regions is the Al & MgF₂ design, which normally offers 85-92 percent reflection in the wavelength region above 200nm and is suitable for use in reflectors for many applications. However, new applications incorporating multielement optical systems have created a need for a superior broadband UV-reflective coating. Figure 4 shows the approximate decrease in the throughput for multielement optical systems with coatings of varying reflectivities.

Obtaining maximum UV throughput from 250nm to 360nm was the main objective when designing a superior broadband UV-reflective coating. Computer-aided thin film design made it possible to simulate several new dielectric coatings over an aluminum base layer to find the optimum combination. Coatings of this type can offer 96 percent or more average reflectance from 250nm to 360nm, which enables one mirror to operate at the 248nm, 282nm, 308nm, and 353nm excimer wavelengths with high efficiency. In addition,

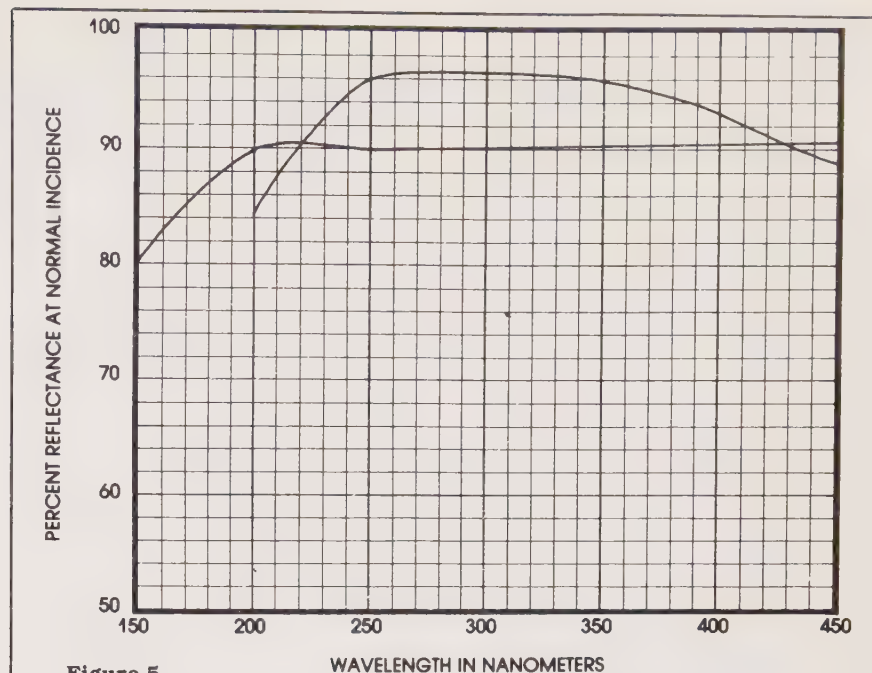


Figure 5.

The upper curve shows average reflectance of a superior broadband-UV coating optimized for use from 250 to 360nm. The lower curve is UV-optimized Al&MgF₂.

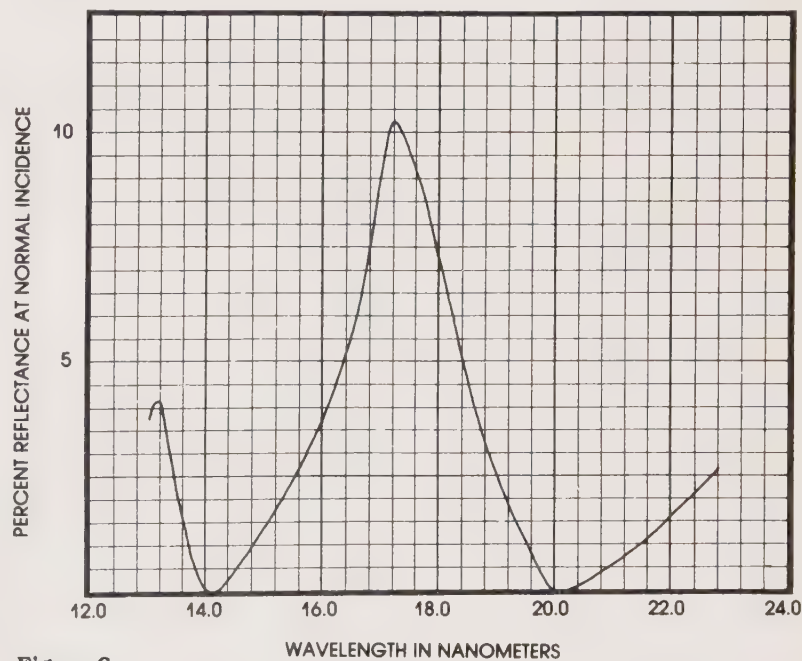


Figure 6.

Percent reflectance of a soft x-ray multilayer mirror measured at near-normal incidence.

tion, visible reflectance is approximately 70 percent, which makes alignment with a visible source easy. Although no damage threshold information is yet available, it is expected that this superior broadband UV coating will easily surpass typical Al&MgF₂ designs (Figure 5).

By using soft x-ray multilayer coatings, normal incidence reflectors can be produced with high efficiency: Up to 30 percent normal inci-

dence reflectance may be attained, compared to less than 1 percent for most other coatings used at normal incidence in this region. Figure 6 shows actual normal incidence reflectance measured from a mirror optimized for use at 17.2nm. Measurements of soft x-ray multilayers produced to date show that they typically offer high efficiency over a very narrow band.

Michael Case
Acton Research Corp.

How to Specify Optical Coating Equipment

Your ability to write well-considered specifications for optical coating equipment is a critical part of making sure that the equipment meets your coating requirements. Too often, purchasers of such equipment are frustrated by either slow vendor response to requests for quotes on a system or poorly detailed proposals — or both. But it's a two-way street. Vendors face their own frustrations in the form of both over- and under-specification of systems by potential customers.

Extremely detailed specifications are often written without considering process requirements, which can lead to expensive vendor quotations and custom engineering to meet specifications not justified by such requirements. Too brief specifications, on the other hand, may only take one specific product or process into consideration, providing the vendor with only enough raw material for a very limited or inferior technical proposal.

Our discussion here is limited to bell-jar and box-coater systems in the 18-inch to 48-inch range. We have also assumed that deposition will be by evaporation with electron-beam and/or thermal sources. However, many of the general guidelines and specification outlines apply to sputtering, ion plating, ion beam systems and other equipment.

Our discussion of the specification process includes several key steps enroute to a general checklist for optical coating system specification. The first is a discussion of the primary needs for system specification. The second is a detailed checklist of coating performance specifications (Table 1). The third is a "shopping list" of subsystem features and performance specifications that might be necessary (Table 2). Table 3 is the final result of the whole specification process.

What do you want to do?

Before determining what type of specification to use and how detailed to be, the specification writer must determine, as accurately as possible, why the machine is being purchased and what it will have to do. While this might seem as indisputable and obvious as motherhood and apple pie, too many specifications ask for

items that are not required or cost-justified for their process, or ignore future needs, or leave out critical elements. The appropriate level of detail for the specification varies according to exactly what one is trying to accomplish. For a production system dedicated to a specific process or substrate, specifications can be less detailed, because the only concern is that the coated product meet its performance requirements. In this case, equipment features and processes may be left to the vendor.

Other cases demand much more detail. For instance, if you are duplicating equipment already in use, your specifications should list specific manufacturers and part numbers for many subsystems, and a high degree of overall detail. Yet another decision must be made when the coating process has not yet been precisely determined by the customer. In this case, you must decide whether to purchase process knowledge and advice from the equipment vendor or to buy a machine with general capabilities and undertake process development in-house.

How much should you tell the vendor?

Once you determine exactly what you want to do with a coating system, you must decide how much specific information to provide the vendor. Obviously, the more information you make available, the more efficient and directed the vendor can be in his response. This saves the all-too-common string of time-wasting phone calls and face-to-face meetings that can be required before the vendor has enough information to make a comprehensive and sensible proposal. Remember, no matter how much equipment and process experience a vendor has, he cannot apply it if he does not understand your problems and objectives.

If new process ideas or equipment configurations are of interest to you, tell the vendor that there are certain areas of the design that are open for suggestions. On the other hand, if you are sold on a particular subsystem or component, be sure to include this information so that the vendor does not waste time configuring his proposal with something else.

The five specification types

Five types of specifications may be included in a coating equipment procurement document. These should be understood in terms of cost impact and possible inconsistencies between specifications. The five types are:

- *Coating performance* — reflectivity, transmission, adherence, abrasion resistance, etc. These are independent of the process or system characteristics (size, sources, etc.). For example, 95% reflectivity at 632.8nm could be obtained with a dielectric stack, enhanced aluminum or silver;

- *Productivity/cost* — substrate size, number to be produced per hour/shift/day, operating costs, etc. Again, these are independent of machine or process features;

- *Equipment performance* — pumping speed, ultimate vacuum, leak-up rate, heating time, planetary capacity, uniformity, required deposition rate, repeatability of thickness control, etc.;

- *Equipment characteristics* — definitions of specific features or actual manufacturers' model numbers for the equipment or subsystems desired;

- *Administrative* — the delivery dates, payment terms, final acceptance test procedures, point of acceptance, etc.

Note that many successful systems have been purchased by only addressing the first two types. It is not unreasonable to leave machine and process characteristics up to the vendor if you are only concerned with achieving acceptable quality in the proper quantities at the proper costs.

Performance/productivity

Coating performance specifications are summarized in Table 1. The table includes relevant tests and paragraphs from MIL-SPECS and other requirements typically called out. Calling out this type of specification increases the likelihood of receipt of a functional system, but at increased cost. If the vendor must set up the system and trim the process to meet the specifications, engineering costs and risk costs will be reflected in the quotation. If you have your own competent thin film

engineers or technicians, it may be more economical and quicker to have them work closely with the vendor on process details, but at the same time not assign complete responsibility for the process to the vendor.

Productivity/cost specifications are straightforward. Typical parameters include: the number of runs per day, shift or week; number of pieces per run; and yield requirements. The size of the pieces, allowable jig marks and substrate mater-

ial must also be specified. It is very important to understand that if only coating performance and productivity specifications are provided the vendor, the vendor will be free to select the process, and will not be constrained by the purchaser's desires.

TABLE 1. POSSIBLE COATING PERFORMANCE SPECIFICATIONS

I. MIL Specs

A. MIL-M-13508C

Test	Requirement
Temperature Influence (4.4.4) — 5 hours at each -80°F and +160°F	(3.7) — visual examination, no signs of deterioration or removal
Hardness (4.4.5) — 50 strokes, 1 lb. weight on 3/8" clean dry cheesecloth	(3.8) — visual examination, no signs of deterioration such as streaks or hairline scratches
Adherence (4.4.6) — "Scotch tape" test, <u>slow</u> pull of <u>clear</u> tape	(3.9) — visual examination, no film removal
Humidity (4.4.7) — 24 hours at 120°F, 95–100% relative humidity	(3.10) — visual examination, no evidence of corrosion or pitting
Salt Spray — Federal Test Method, Std. No. 151, which references ASTM B117	(3.10) — visual examination, no evidence of corrosion or pitting

B. MIL-C-675C

Salt Solubility (4.5.7) — 24 hours submission in NaCl solution	(3.8.4.1) — no visible evidence of abrasion or coating removal after severe abrasion test (perform on witness piece)
Humidity (4.5.8) — test same as MIL-M-13508C — (4.4.7)	(3.4.1) — no evidence of deteriorations such as flaking, peeling, cracking or blistering <u>and</u> (3.8.4) — meets severe or moderate abrasion as appropriate to substrate Knoop hardness
Salt Spray Fog (4.5.8) — 24-hour exposure to salt fog per ASTM B117-73	(4.5.31) — visual examination for flaking, peeling, cracking or blistering <u>and</u> (4.5.10) — no visual evidence of abrasion or coating removal after severe abrasion test (perform on witness piece)
Severe Abrasion (4.5.10) — 20 cycles (40 strokes), force of 2.0–2.5 lbs. with "std" eraser (used for substrates with Knoop hardness over 450kg/mm ² or witness piece)	(3.8.4.1) — no visible damage such as coating removal
Moderate Abrasion (4.5.11) — same as "hardness" in MIL-M-13508C: 50 strokes, 1 lb., clean, dry cheesecloth	(3.8.4.2) — no visible damage such as coating removal
Adhesion (4.5.12) — "Scotch tape" test with <u>clear</u> tape; but removed <u>quickly</u>	(3.8.5) — no evidence of coating removal

C. MIL-C-14806A

Test	Requirement
Humidity "B" and Abrasion (same as Humidity of MIL-C-675C)	(3.4.1) — no evidence of deteriorations such as flaking, peeling, cracking or blistering <u>and</u> (3.8.4) — meets severe or moderate abrasion as appropriate to substrate Knoop hardness
Salt Fog — test per MIL-STD-810 Method 509-I, 48 hours exposure to salt fog (from 5% salt solution) at 95° F	(3.6.1) — no evidence of flaking, peeling or blistering
Humidity "C" — test per MIL-STD-810 Method 507-I except exposure time should be 48 hours continuous at 85-95% RH and temperature 82° F to 160° F	(3.6.3) — no evidence of a cloudy or hazy appearance
Abrasion — same as <u>severe</u> abrasion of MIL-C-675C	(3.6.1) — no evidence of flaking, peeling or blistering

D. MIL-C-48497 (MU 27, June, 1974)

Durability requirement for interference coating; single or multilayer — this specification has similar tests to the above specifications; adhesion, humidity, abrasion, etc. The major difference is that the tape adhesion, 24-hour humidity, and moderate abrasion tests must be applied sequentially to one witness piece.

II. Spectral Performance

- A. Reflection, transmission and absorption requirements
- B. Angle of incidence
- C. Polarization
- D. Wavelength
- E. Laser damage requirements

III. Substrate Characteristics

- A. Material
- B. Size
- C. Jig marks
- D. Index of refraction

IV. Cosmetic Specifications

- A. Pinholes
- B. Scratch and dig (per MIL-M-13830A)
- C. Smears, discoloration, etc.

If you want the vendor to be constrained by your process desires, you must be very specific, and include equipment performance and feature specifications.

Equipment performance: specifications and features

There is a long list of equipment performance specifications available to the coating system purchaser. Table 2 details many of these, along with analogous equipment features. In this realm, you must be sure not to produce performance specifica-

tions inconsistent with your equipment features. For instance, if you tell a vendor to use a particular instrument, you must live with the capabilities of that instrument. You can't go on to specify the performance you would like to see from the instrument.

When actual equipment features are specified, significant problems can crop up, and a common result is higher costs. By being too specific here, the user can inadvertently eliminate other, sometimes less costly alternatives, and it may result in

money spent on a noncritical feature. But as with other specifications, the results of being too brief can also be negative, especially when it involves a critical feature of the system.

In general, detailing equipment performance specs and features is the most time-consuming and important part of the entire specification writing procedure. Frequently, a customer will prepare a draft specification for vendor comment and approximate pricing before final negotiation and definition of specs.

TABLE 2. CHECKLIST OF SUBSYSTEM ITEMS AND CHARACTERISTICS FOR USE IN SYSTEM SPECIFICATION

Chamber

- chamber size determined by product geometry, quantity and coating process;
- accessibility;
- additional feedthroughs, sight ports;
- space constraints; height, width, depth, baseplate height;
- chamber water-cooling (cold, warm, switching required?);
- cryogenic and water-cooled baffles;
- H.V. valves (vertical or horizontal, evaporant shields);
- heat shields, shutters, fixturing, etc;
- bellows sealed valves versus "O" ring seals.

Pumping System

- base pressure/pumping time (specify chamber conditions, hot or cold);
- pumping fluids to be compatible with process gases;
- conventional mechanical/diffusion pump system;
- LN₂ (consider consumption rates), mechanical refrigeration, water baffles;
- cryopump system (size, type of gases to be pumped; time between regeneration).

Planetary/Rotating Fixture

- planetary or single rotation of flat or domed fixtures (determined by component size, quantity and uniformity requirements);
- performance specs (operating temperature, maximum load capacity, maintenance schedule, etc);
- "flip" fixturing;
- planetary design features (angled or flat, height adjustable, water-cooling, size of drive feedthroughs);
- drive mechanism (gears/chain/friction).

Gauging

- ionization/cold cathode gauges — how many readouts, sense positions, and set-points? remote-selectable? signal output desired;
- capacitance manometer;
- thermocouple gauges — roughing, fore-line, crossover, etc.; selectable or continuous display.

Gas Controls

- multiple gases? mixing?
- control philosophy: control gas admittance or pumping speed throttling; feedback control required?;
- which gauge to control from — ionization, capacitance manometer, thermocouple?;
- feedback from R.G.A. for precise composition control;
- control valve — servo needle valve or piezoelectric.

Deposition Process

- resistance sources and/or electron-beam gun determined by process and production requirements;
- resistance sources:
 - how many, what size feedthroughs?;
 - power supply size (voltage, fixed or selectable?);
 - SCR or Variac control?;
 - source holder details;
 - automatic post selection.
- electron-beam gun:
 - type and size;
 - single or multiple crucible?;
 - beam sweep configuration;
 - position within chamber adjustable?;

Deposition Control

- rate — by quartz crystal monitor;
 - how many sensors, locations?;
 - define maximum sensitivity and thickness of total layers in multilayer applications;
 - water-cooled sensor heads/double heads for increased reliability;
 - thickness, rate signals/setpoints, etc;
- end point detection by optical monitor;
 - reflection/transmission;
 - monochromator or narrow bandpass filters (wavelength ranges, gratings, how selected or changed);
 - type of detection electronics;
 - VIS/IR detection;
 - how much sensitivity required?;
 - chip changer — how many pieces?;

Heat

- heater type ("calrod"/quartz lamp) and location;

- heat power requirements (voltage, isolation transformer);
- control (soft start, proportional control, "ramp up and down," how many and type thermocouples), setpoints front panel selectable?

Glow

- glow current and voltage requirements;
- arc suppression/short circuit protection;
- type of gas controls;
- glow electrode configuration.

Automation

- partial or complete — pumping cycle, heating, rotation, interlock versus complete deposition process;
- programmability — machine set up for one process, or need to reprogram new processes;
- use of programmable controller (sequencing, timing, etc.) versus computer (calculations, control, data logging);
- subsystem/computer interactions;
 - computer to "turn on" subsystems which control independently or computer to measure variables and control directly;
 - control setpoints — set and variable by computer or set manually on front panel;
 - interfaces — RS-232, IEEE-488, or computer back plane, direct inputs (A/D converters, etc.)
- data logging;
 - which parameters, how often sampled;
 - recording medium;
 - accessibility to operator to monitor process in real time.

Safety/Maintainability

- "bellows safety switches" for all high voltage supplies;
- main door interlock to disable all deposition related functions?;
- interlocks for air, cooling water, others?;
- maintenance mode override of interlocks;
- emergency switch;
- maintenance schedule/time required for daily/weekly/monthly maintenance.

**TABLE 3. AN OUTLINE FOR TYPICAL
OPTICAL COATING SYSTEM SPECIFICATION**

General Equipment Description

- A. Equipment use (R & D, dedicated production, job shop use, etc.)
- B. Type of coatings to be produced.
- C. Responsibility for process development (vendor or purchaser).
- D. Summary of major subsystems.

Administrative Requirements

- A. Time to respond to quotation.
- B. Whom to respond to; address, phone number and number of copies required.
- C. Person to direct technical questions to (phone number).
- D. Method of handling bids:
 - 1. Negotiated.
 - 2. Firm fixed price bid; subsequent negotiation.
 - 3. Firm fixed price to be placed with lowest cost technically acceptable proposal.
 - 4. Preliminary cost estimates only required.
- E. System delivery required.

Pricing

- A. Subsystem pricing required.

- B. Options to be costed separately.
- C. Payment terms — progress payments, cash discounts.
- D. Time for which cost proposals must be fixed.
- E. Shipping point; F.O.B. factory or customer facility.
- F. Delivery and installation responsibilities.
- G. Manufacturer's warranty.

**Coating Performance Specifications
Detailed**

- A. MIL specs required.
- B. Spectral performance.
- C. Substrate characteristics.
- D. Cosmetic specifications.

Productivity Requirements

- A. Substrate size.
- B. Quantities/hour, day, shift, etc.
- C. Production cost requirements.

**Equipment Performance and
Feature Specifications**

- A. Chamber.
- B. Pumping system.
- C. Sources.

- D. Gauging.
- E. Glow discharge.
- F. Heat.
- G. Gas Controls.
- H. Monitoring systems.
 - 1. Optical Monitor/Test Glass Changer/Strip Chart Recorder.
 - 2. Quartz Crystal Monitor.
 - 3. RGA.
- I. Automation.
 - 1. Pumping.
 - 2. Process controls.
 - 3. Data logging.

**Vendor Responsibility
After Delivery**

- A. Spare parts.
- B. Training.
- C. Documentation to be delivered:
 - 1. Operating manuals.
 - 2. Maintenance manuals.
 - 3. Drawings.

Acceptance Tests

- A. Details of acceptance tests.
- B. Point of acceptance tests (vendor's or purchaser's facility).

**Administrative specifications,
design and construction**

Administrative specifications are frequently overlooked. Many of them are straightforward, but they can have dramatic cost impact. For instance, acceptance test procedures can be extensive and require the vendor to budget extensive engineering time. Extensive installation and on-site training will also drive costs up. When a great degree of expediting, progress reporting and engineering approval is required, costs again can rise.

Table 3 contains an outline of a typical general equipment specification. Obviously, many specifications will not have to include all of these items, but this will serve as a checklist to avoid omitting critical items.

Once a specification is prepared and a purchase order is ready to be placed, the vendor's quotation and the specification must be checked for inconsistencies. Frequently the purchaser will accept standard vendor components that do not meet the letter of the specification, but are quite acceptable. These should be

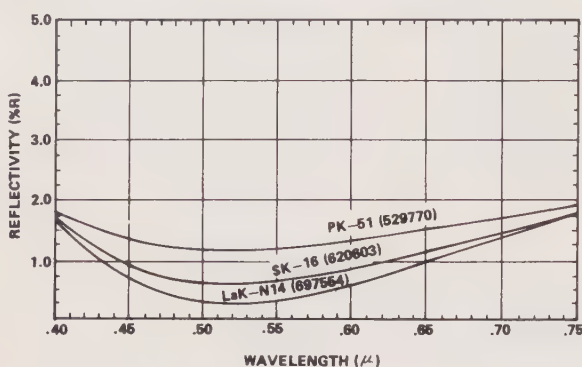
noted to avoid future confusion and possible misunderstandings.

A purchaser must next determine how closely to interface with the vendor during the design and manufacturing effort. Detailed and frequent reviews at project start can help guarantee that you receive precisely the system you desire. If detailed effort was devoted to the original specification, design reviews should be straightforward and primarily involve review of details.

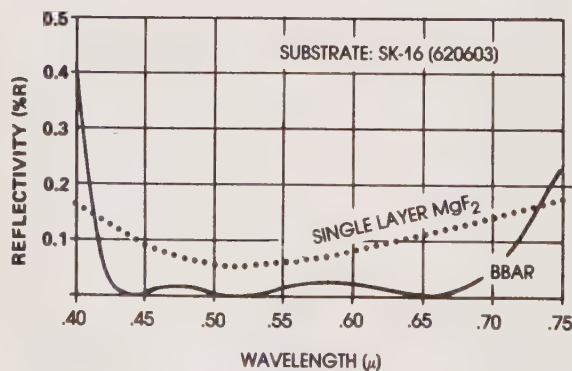
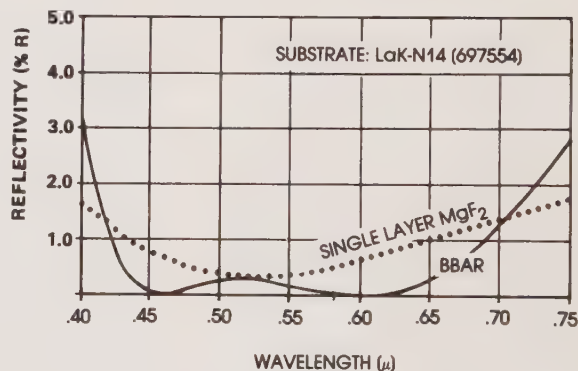
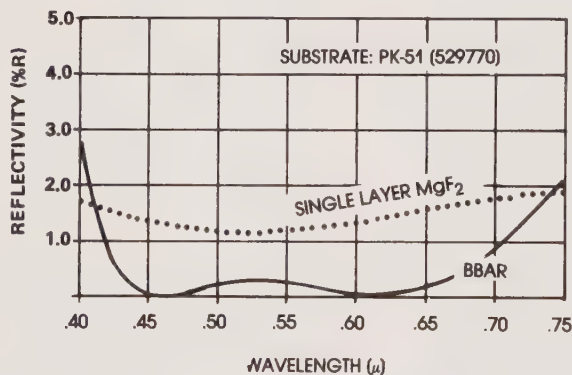
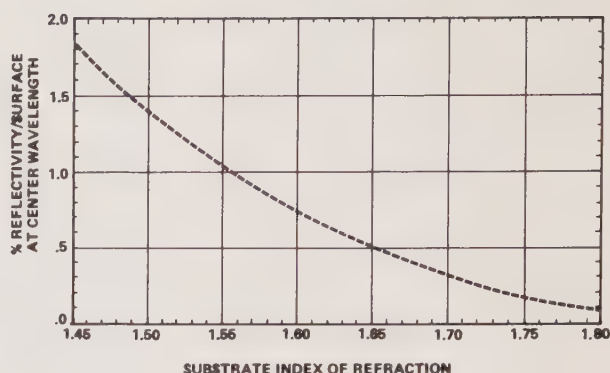
*Peter Denton & Bawa Singh
Denton Vacuum*

Reflectivity of Various Glasses with BBAR* or MgF_2 Coatings

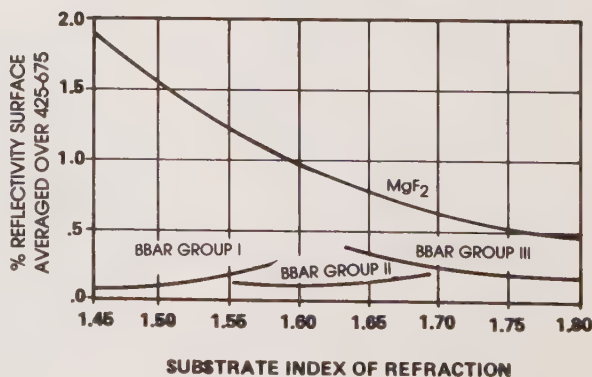
MgF_2 ON VARIOUS SUBSTRATES



REFLECTIVITY AS A FUNCTION OF INDEX OF REFRACTION



REFLECTIVITY AS A FUNCTION OF INDEX OF REFRACTION

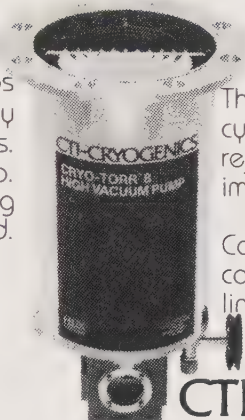


SOURCE: GCA TROPEL INC.

*BBAR = Broad Band Antireflection Coating

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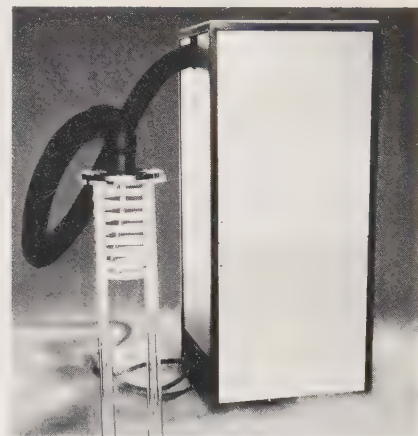
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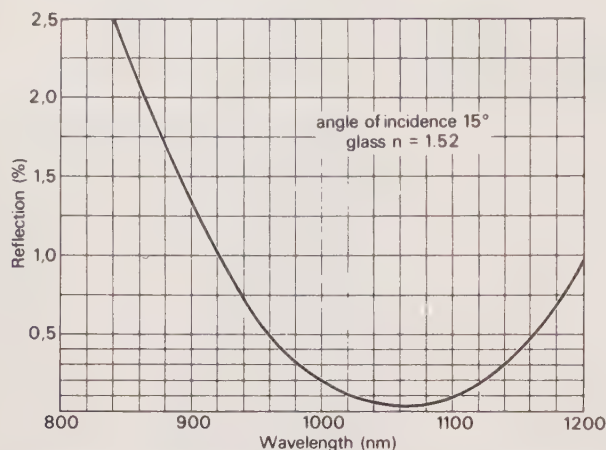
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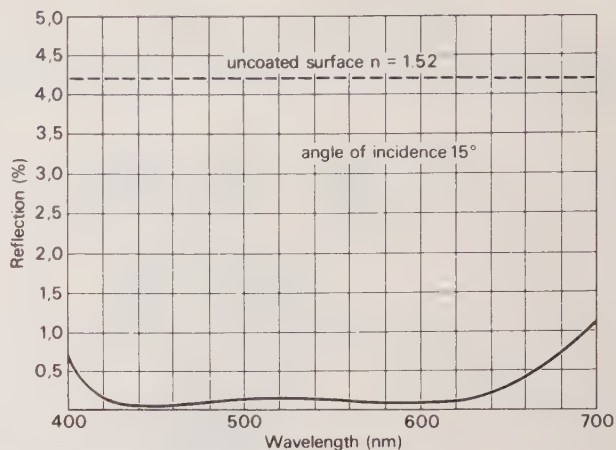
Antireflection Coatings for the Ultraviolet, Visible and Near-IR

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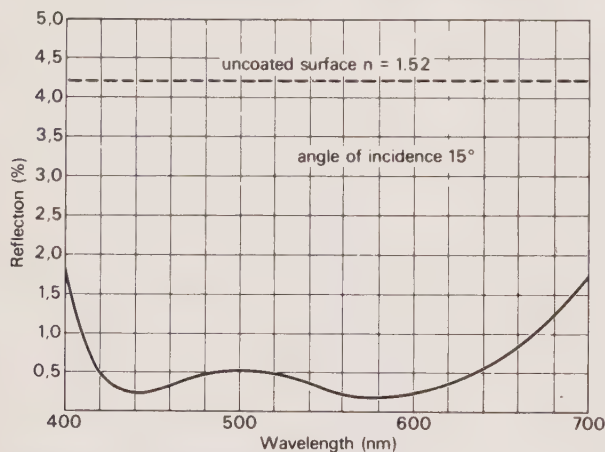
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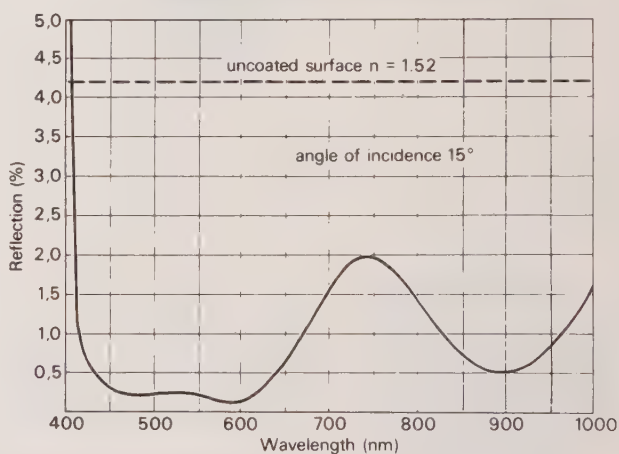
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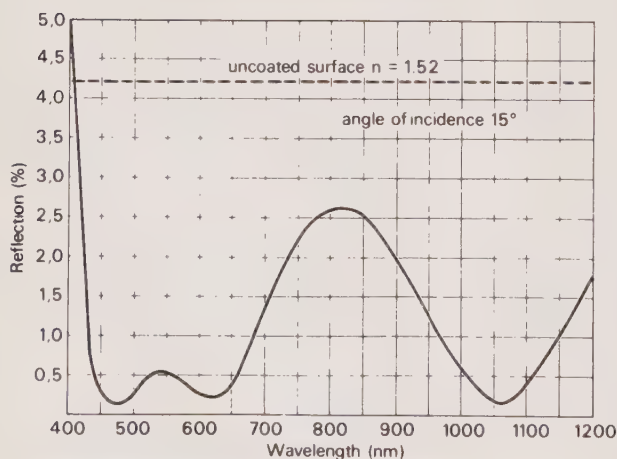
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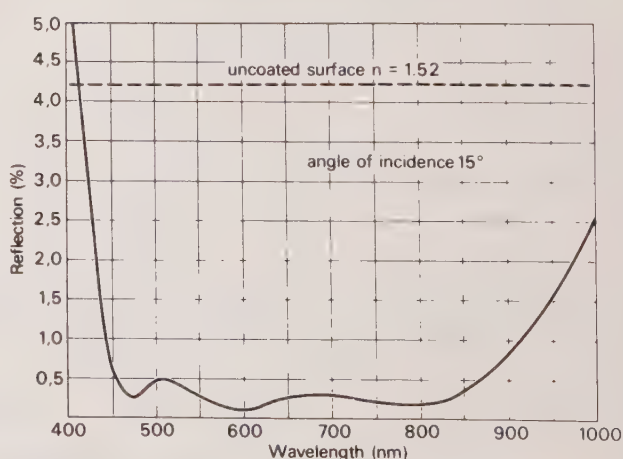
Representative Application: Rangefinder systems

VISIBLE PLUS LASER LINE (1.06μ)



Representative Application: Rangefinder systems

BROADBAND AR COATING



Representative Application: Night vision systems (near IR)

SOURCE: BALZERS CORP.

Detectors

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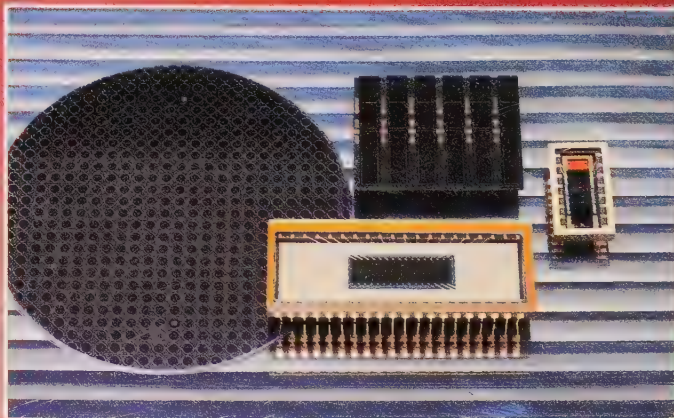
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Typical Photocathode Spectral Response

Semitransparent Photocathodes (Transmission Mode)

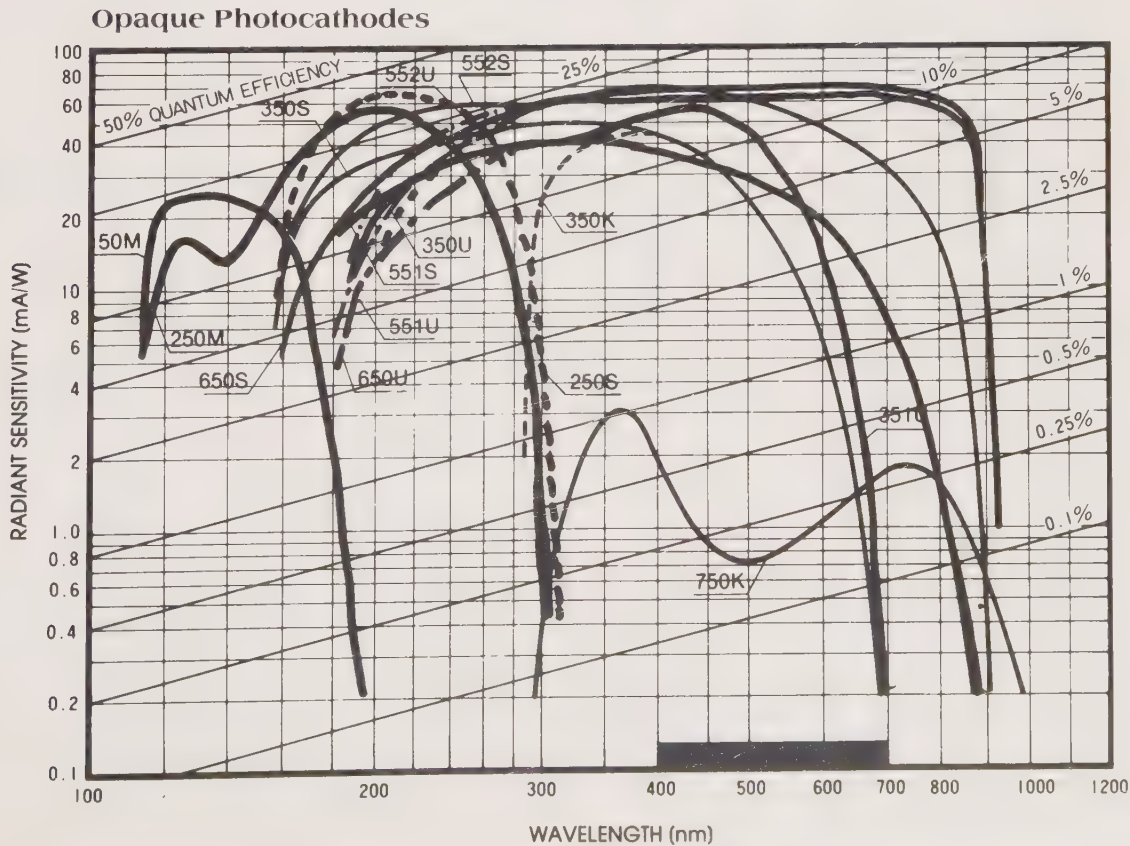
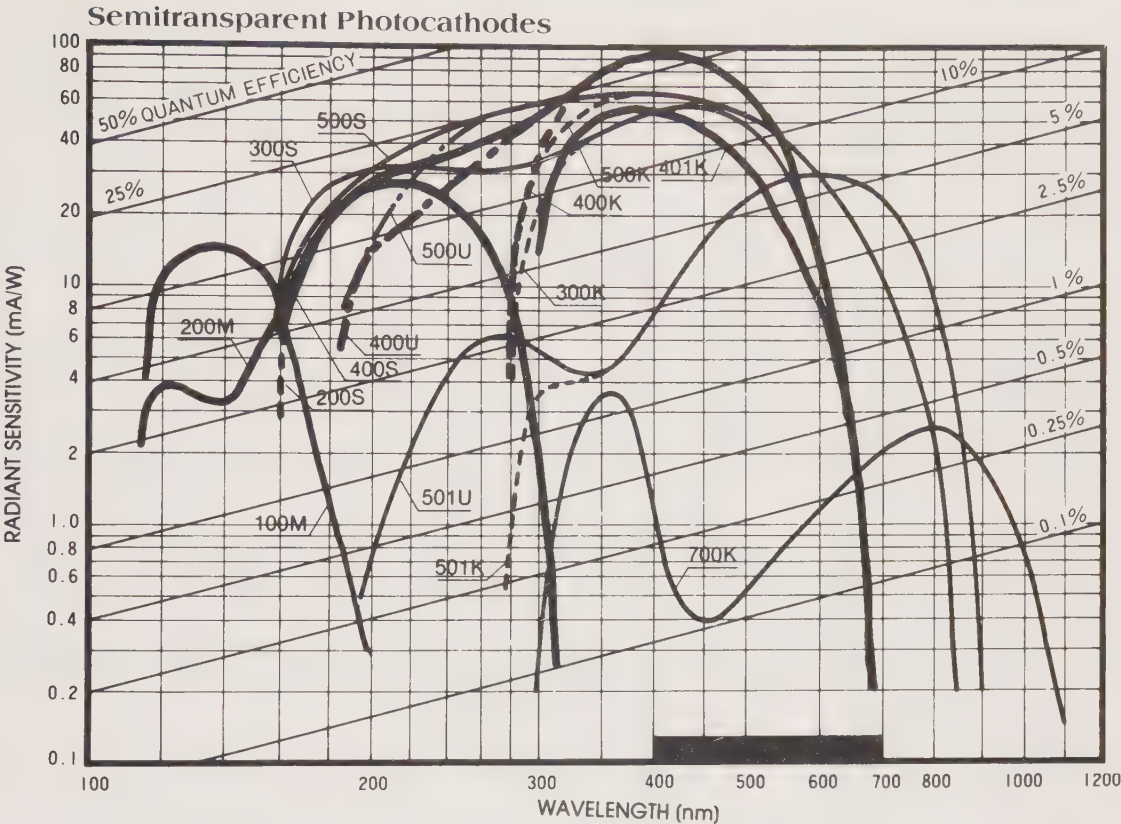
Curve Codes (see curves to right)	Photocathode Materials	Window Materials	Spectral Response		
			Range (nm)	Peak Wavelength	
				of Radiant Sensitivity (nm)	of QE (nm)
100M	Cs-I	MgF ₂	115 ~ 200	140	130
200S	Cs-Te	Fused silica	160 ~ 320	210	200
200M	Cs-Te	MgF ₂	115 ~ 320	210	200
300K (S-11)	Sb-Cs	Borosilicate	300 ~ 650	440	410
300S (S-13)	Sb-Cs	Fused silica	160 ~ 650	440	200
400K	Bialkali	Borosilicate	300 ~ 650	420	390
400U	Bialkali	UV glass	185 ~ 650	420	390
400S	Bialkali	Fused silica	160 ~ 650	420	390
401K	High temp. bialkali	Borosilicate	300 ~ 650	375	360
402K	Bialkali	Borosilicate	300 ~ 650	375	360
500K (S-20)	Multialkali	Borosilicate	300 ~ 850	420	360
500U	Multialkali	UV glass	185 ~ 850	420	290
500S	Multialkali	Fused silica	160 ~ 850	420	280
501K	Multialkali	Borosilicate	300 ~ 900	650	600
501U	Multialkali	UV glass	185 ~ 900	650	600
502K	Multialkali	Borosilicate	300 ~ 840	420	360
700K (S-1)	Ag-O-Cs	Borosilicate	400 ~ 1200	800	780

Opaque Photocathodes (Reflection Mode)

150S	Cs-I	Fused silica	153 ~ 195	165	165
150M	Cs-I	MgF ₂	115 ~ 195	120	120
250S	Cs-Te	Fused silica	160 ~ 320	200	200
250M	Cs-Te	MgF ₂	115 ~ 320	200	190
251U	Cs-Te	UV glass	185 ~ 300	220	220
350K (S-4)	Sb-Cs	Borosilicate	300 ~ 650	400	350
350U (S-5)	Sb-Cs	UV glass	185 ~ 650	340	270
350S (S-19)	Sb-Cs	Fused silica	160 ~ 650	340	210
351U (Ext'd S-5)	Sb-Cs	UV glass	185 ~ 700	450	235
450S	Bialkali	Fused silica	160 ~ 700	400	190
451U	Bialkali	UV glass	185 ~ 730	340	320
452U	Bialkali	UV glass	185 ~ 750	350	315
453K	Bialkali	Borosilicate	300 ~ 650	400	360
453U	Bialkali	UV glass	185 ~ 650	400	330
454K	Bialkali	Borosilicate	300 ~ 680	450	430
550U	Multialkali	UV glass	185 ~ 850	530	250
550S	Multialkali	Fused silica	160 ~ 850	530	250
551U	Multialkali	UV glass	185 ~ 870	330	280
551S	Multialkali	Fused silica	160 ~ 870	330	280
552U	Multialkali	UV glass	185 ~ 930	400	260
552S	Multialkali	Fused silica	160 ~ 930	400	215
553K	Multialkali	Borosilicate	300 ~ 850	400	400
554U	Multialkali	UV glass	185 ~ 930	450	370
555U	Multialkali	UV glass	185 ~ 850	400	320
555S	Multialkali	Fused silica	160 ~ 850	400	320
650U	GaAs	UV glass	185 ~ 930	300 ~ 800	300
650S	GaAs	Fused silica	160 ~ 930	300 ~ 800	280
651U	GaAs	UV glass	185 ~ 910	350	270
651S	GaAs	Fused silica	160 ~ 910	350	200
750K	Ag-O-Cs	Borosilicate	400 ~ 1100	730	730

Source: Hamamatsu Corp.

Typical Photocathode Spectral Response Curves



Silicon Photodiodes: Making the Right Choice

Choosing the right silicon photodiode for your light-sensing application can be a complex procedure. To make the right choice, it is necessary to know the photodiode parameters required for your unique situation — its light levels, wavelength and geometry. This “layman’s” article describes most of the important photodiode performance concepts, and offers the user some general selection guidelines.

A silicon photodiode, a solid-state device that converts incident light into an electric current, consists of a shallow diffused pn junction, normally a p-on-n configuration. Diffused silicon sensors are usually of two types, depending upon their processing method, namely planar diffused or mesa structures.

In the p-on-n planar diffused configuration shown in Figure 1, the junction edge emerges on the top surface of the silicon chip, where it is passivated by the thermally-grown oxide layer. In mesa structures (Figure 2), the active area extends all the way across the top surface of the chip. The junction edge emerges at the side of the chip without any thermal oxide passivation. This configuration is usually less expensive but is recommended only for photovoltaic operation and only when signal-to-noise is not a concern.

The equivalent circuit of a photodiode is fundamentally a current generator. The flow of the current develops a load voltage that forward-biases the ideal diode. The junction capacitance depends upon the applied reverse bias being large at zero bias and decreasing as reverse bias voltage is applied.

The shunt resistance is a high value, but is an inverse exponential function of forward voltage. The series resistance is low, this being a design function of the diffusion processes and terminations.

Spectral response

Silicon photodiodes are typically sensitive to light in the spectral range from about 350nm in the near-ultraviolet (UV), through the visible, to 1050nm in the near-infrared (IR). Special device designs can extend responsivity further into the ultraviolet or infrared. Photosensor responsivity (R) is measured in amperes (A) of photocurrent generated per watt (W) of incident light power.

Actual light levels range typically from picowatts to milliwatts, which generate photocurrents from picoamps to milliamps. Responsivity in amps/watts varies with the wavelength of the incident light, with peak values from 0.5 to 0.7 A/W. Silicon photodiode response is well matched to light sources emitting in the red to violet visible spectrum, as well as for HeNe lasers, GaAlAs and GaAs LEDs and laser diodes, and Nd:YAG lasers.

The silicon photodiode response is usually linear within a few tenths of a percent from the minimum detectable incident light power up to one milliwatt. Response linearity improves with increasing applied reverse bias and decreasing effective load resistance.

Heating the silicon photodiode shifts its spectral response curve (including the peak) to the right toward longer wavelengths; cooling shifts the curve to the left toward shorter wavelengths. The following values are typical for the temperature dependence of responsivity:

- a) $+0.75$ to $0.9\%/^{\circ}\text{C}$ at $1.064\mu\text{m}$;
- b) $\sim 0\%/^{\circ}\text{C}$ below and near the peak;
- c) -0.1 to $-0.2\%/^{\circ}\text{C}$ in the blue.

Speed of response

The 10% to 90% rise times for a silicon photodiode include charge collection, RC, and diffusion-time components. In addition, the bandwidth limitations of the associated

amplifier must be considered. Rise time values for commercially available, nonavalanching pin and pn silicon photodiodes range from under 1nsec for small-area devices operating in the photoconductive (reverse-biased) mode into a small load resistance, up to several μsec for large-area cells operating in the photovoltaic (zero-biased) mode.

Noise

Photodiode noise current has two main components: shot noise and thermal (Johnson) noise. In addition, it's important to consider the various noise components of the amplifier into which the photodiode is operating. A thorough understanding of system noise is particularly useful in low-light-level systems where incident light powers are as low as 10^{-14} to 10^{-15}W . Under most operating conditions, thermal noise is the dominant noise source.

Figures of merit

Quantum efficiency η would be 100% if each photoexcited electron-hole pair were collected, thus contributing to the photocurrent flowing through an external load.

$$\eta = \frac{1.25R}{\lambda}$$

R = Photodiode responsivity, A/W

λ = Wavelength of irradiance, μm

$R = 1 \text{ A/W}$ at $\lambda = 1.25\mu\text{m}$ if $\eta = 100\%$

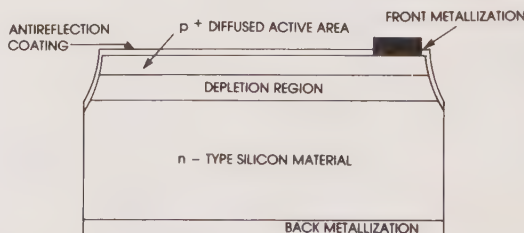


Figure 1.
Planar diffused
pn junction
silicon sensors.

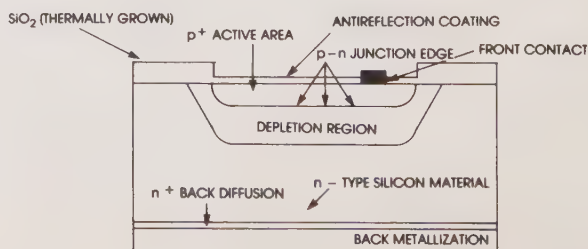


Figure 2.
Mesa diffused
pn junction
silicon sensors.

Silicon Photodiodes

It can be seen from spectral response curves that quantum efficiency values in the range from 50% to 90% are typical depending upon the wavelength of the incident light and the detector series.

Noise equivalent power (NEP) is the incident light power for which the signal-to-noise ratio is just equal to 1, and thus is a measure of the minimum detectable light power.

$$NEP \cong i_n / \sqrt{B} R$$

i_n = Total noise current, (A)(rms)

B = Operating bandwidth, Hz

R = Photodiode responsivity, A/W

Photodiode NEP values range from about $10^{-15} \text{ W}/\sqrt{\text{Hz}}$ for small-area low-noise silicon photodiodes to over $10^{-12} \text{ W}/\sqrt{\text{Hz}}$ for large-area cells.

For a photodiode/op-amp combination, the output signal voltage:

$$(V_s) = P_{inc} R R_f$$

where

P_{inc} = Light power incident on photodiode active area, W

R = Photodiode responsivity at wavelength of incident light, A/W

R_f = Feedback resistance

It follows that

$$P_{inc} = \frac{V_s}{R R_f} = \frac{2\pi B C_f V_s}{R}$$

Since NEP is the minimum detectable incident light power at which total noise voltage (V_n) just equals signal voltage (V_s), we have a new expression for NEP:

$$P_{inc}^{MIN} = NEP = \frac{2\pi B C_f V_n}{R}$$

Detectivity (D^*) is a measure of detector signal-to-noise ratio, normalized for detector active area and bandwidth:

$$D^* = \frac{\sqrt{AB} R}{i_n} = \frac{\sqrt{A}}{NEP} \cdot \text{cm} \sqrt{\frac{\text{Hz}}{\text{W}}}$$

Detectors

A = Photodiode active area, cm^2

B = Operating bandwidth, Hz

R = Photodiode responsivity, A/W

i_n = Total noise current, (A)(rms)

D^* values from 10^{11} to $10^{13} \text{ cm} \sqrt{\text{Hz}/\text{W}}$ can be expected for silicon photodiodes.

How to specify

As indicated earlier, selection of a silicon photodiode to meet your application can be a perilous process. The following procedure will give the neophyte some general guidelines suitable for most applications. Keep in mind that a good vendor has a large amount of flexibility in his products and can usually meet your specific requirements.

First, decide on the general size of the device. This may be determined entirely by the physical requirements of the application, or more likely by the type of illumination (focused or flooded), amount of cur-

TABLE 1.
SUMMARY OF SILICON PHOTODIODE PARAMETER INFORMATION

Symbol	Name	Typical Range of Values	Depends On	Design High/Low Value For
R	Responsivity	0.05 A/W - 0.65 A/W	wavelength (λ), design, structure	High for detecting weak light signals
T_{90}^{10}	Rise Times	Under 1nsec - tens of μsec	C_j , ($R_s + R_L$), Q , structure	Low for wide bandwidth
C_j	Junction Capacitance	Few pf - several thousand pf	A , $Q^{1/2}$	Low for fast response + low for low noise
i_n	Noise Current (rms)	10^{-15} to 10^{-11} (A)(rms)/ $\sqrt{\text{Hz}}$	$I_D^{1/2}$, $R_{SO}^{-1/2}$	Low for low NEP + High D^*
I_D	Dark Current	Few pA - $10 \mu\text{A}$	A , $Q^{1/2}$, $V_R^{1/2}$	Low for low shot noise
R_{SO}	Source Resistance	Few tenths Mohm - Several thousand Mohm	A^{-1} , $Q^{-1/2}$, process	High for low thermal noise
η	Quantum Efficiency	Few % - 95%	R , design	High for low NEP + high D^*
NEP	Noise Equivalent Power	10^{-15} - $10^{-11} \text{ W}/\sqrt{\text{Hz}}$	i_n , R^{-1} , $B^{1/2}$	Low for high D^* and detecting weak signals
D^*	Detectivity	10^{11} - $10^{13} \text{ cm} \sqrt{\text{Hz}/\text{W}}$	i_n^{-1} , $B^{1/2}$, $A^{1/2}$	High for high signal-to-noise ratio
A	Active Area	Few tenths mm^2 - several cm^2	Application	Large for high D^*
Q	Bulk Resistivity	Few ohm-cm - several thousand ohm-cm	Application	High for low capacitance
P_{inc}	Incident Light Power	Few μW - several mW	Light source	High for good S/N ratio, $< 1 \text{ mW}$ for good response linearity
R_s	Series Resistance	0.1 ohm - 1000 ohm	Q , A , structure	Low for fast response and a good response linearity
V_R	Reverse Bias Voltage	0.01-100 Volts	Application	Low for low noise, High for high speed and better linearity

rent required and cost. If your volume is small, pick a size that is available as a standard product.

Second, decide on the reverse bias to be used. Whenever possible, choose photovoltaic operation to remove reverse bias leakage current problems, and to lower cost through higher yields and less testing. Use reverse bias only when high frequency response or high output currents are required.

Packaging is also of concern to most customers. In office environments, passivated photodiodes are usually stable enough so that they can be mounted on printed circuit boards or low-cost plastic housings. Higher-technology parts can require custom ceramic packaging or hermetic sealing. Customizing a package to your needs is the common practice, even for small-volume ap-

plications where the tooling for a printed circuit board is low.

The second stage of specifying a photodiode is to pin down exactly what electrical specifications to use. Specify sensitivity in terms of amps per watt at a particular wavelength when you are using LEDs, lasers, or filtered light. Use short-circuit current when illumination is by "white" light from a tungsten lamp at a particular color temperature and illumination level (watts per square centimeter). Since correlation between facilities for footcandle measurements is extremely poor, only on rare occasions is it recommended that sensitivity in terms of short-circuit current at a footcandle illumination be used.

For dark electrical characteristics, keep the tests to a minimum. For instance, in photovoltaic operation,

perhaps specify shunt resistance alone, or in biased operation, specify the dark current at your operating voltage, and occasionally specify breakdown voltage if your operating voltage is high. Other parameters such as capacitance and rise time are usually of little concern.

The emphasis is on interaction between you and the vendor during the design stage of your photosensor needs. Competent vendors can give you assistance in specifying your product, with both cost and performance in mind. Customizing to your application is usually easy, especially if a standard-size product can be used with only packaging and testing unique to your requests.

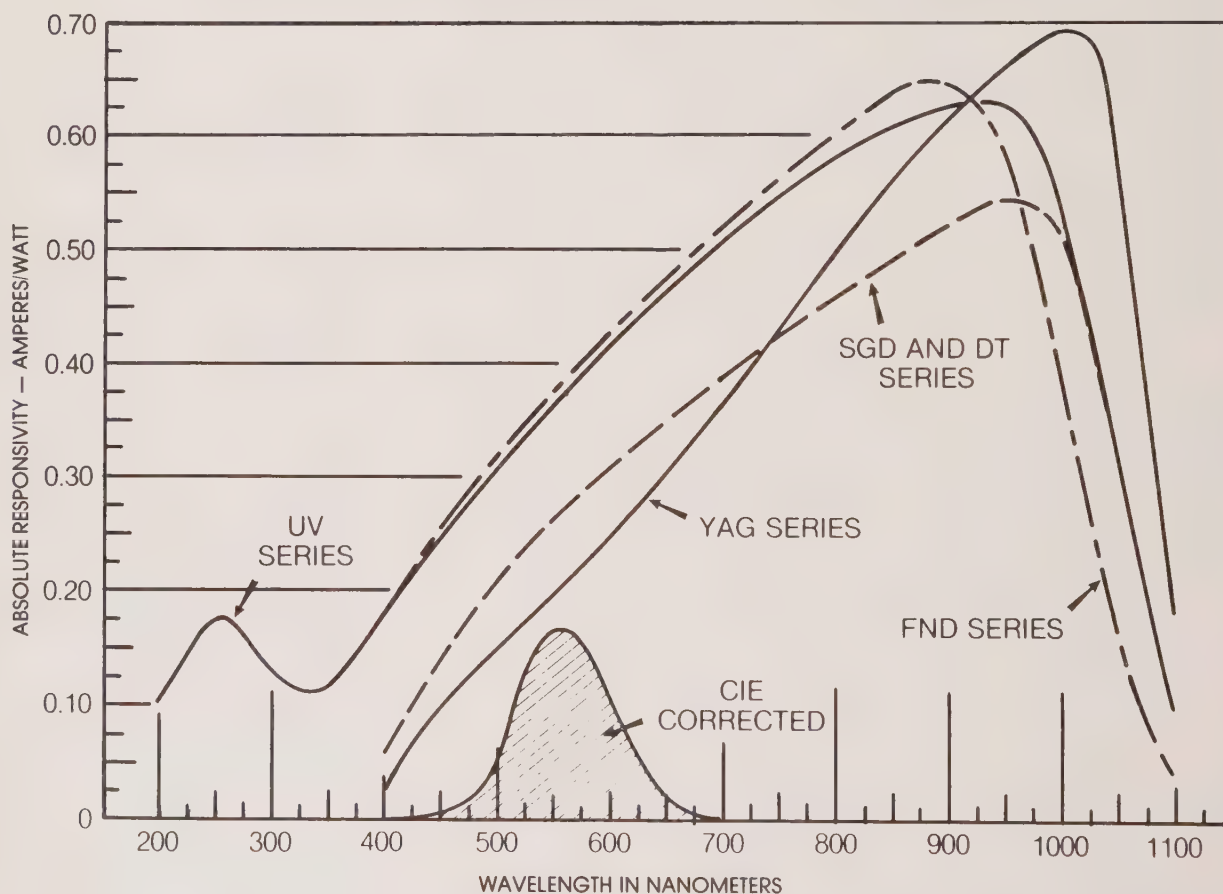
L.A. Godfrey

Advanced Detector Corporation

Div. of

Applied Solar Energy Corp.

Spectral Response of Silicon Photodiodes



The curves above are based on EG&G Electro-Optics photodiode series but are representative of classes. The SGD and DT series are planar-diffused oxide-passivated photoconductors of guard-ring construction, for use with lasers, injection lasers, and in radiation measurement and detection, and navigation and guidance systems. The planar-diffused YAG series is designed to

accompany Nd:glass or Nd:YAG lasers used as radiation sources for guidance, tracking and alignment. The FND series is an ultrafast series for use in fiber optic data links and other fiber optics applications, and laser pulse detection. The UV series are photovoltaic detectors for use in analytical instruments, process control and instrumentation and medical diagnostics.

Fiber Optics

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Fiber Optic Test and Measurement

Measuring optical power

Electromagnetic radiation has both wavelike and particle-like characteristics. When treating the detection process, the particle model dominates; when treating the optical fiber, the wavelike characteristic is dominant. When treating the source, both wavelike and particle-like characteristics are important. Optical power can be thought of as a stream of photon particles, each carrying a bit of energy, the exact amount depending on wavelength.

Decibel units for fiber optics are the logarithmic transformations of the basic optical power unit, watts, and submultiples of watts. Decibel units are useful in compressing power measurement data that has a wide dynamic range. These units are commonly used in fiber optic measurements. Table 1 gives the definitions of decibel units; Table 2 is a conversion listing between dBm and mW (see also the graph in this section).

Dectector types

Solid-state photodiodes are used almost exclusively for fiber optic power meters. The typical wavelength coverage of the most often used types is listed in Table 3.

Power density limit

The relationship between total power out of the fiber and power density on the detector surface is:

$$P_d = P / \pi t^2(NA)^2$$

where: P_d = power density on detector (mW/mm²)

P = output power from fiber = (mW)

t = separation of fiber end and detector (mm)

NA = fiber numerical aperture.

For instance, a fiber with a NA of 0.2, located 1mm from a detector surface and emitting 100 microwatts (0.1mW), would produce a power density on the detector surface of 0.8 mW/mm². Consult the manufacturer's specifications for power density limits. Specifications can be exceeded before the power limit is reached for a fully illuminated detector (see Figure 1).

Measuring attenuation:

Techniques for measuring optical fiber attenuation can be divided into two classes: (1) power meter measure-

**TABLE 1
CLARIFICATION OF
OPTICAL dB UNITS**

Measurements of optical radiation power are expressed in watts. Decibel (dB) power is:

$$dB = 10 \log \left[\frac{P_{sig}}{P_{ref}} \right]$$

where P_{sig} is the power to be measured and P_{ref} is the reference power.

For 1mW reference power:

$$dBm = 10 \log \left[\frac{P_{sig}}{1mW} \right]$$

For 1 μ W reference power:

$$dB\mu = 10 \log \left[\frac{P_{sig}}{1\mu W} \right]$$

With both P_{sig} and P_{ref} variable, the dB-power formula expresses the log ratio of the two unknowns in dB. Light-power loss of an optical data-link element is:

$$L (dB) = 10 \log \left[\frac{P_o}{P_{in}} \right]$$

The input power (P_{in}) and output power (P_o) of a component can be measured in dBm units, dB μ units or dB units without a known reference. The loss L expressed in decibels is the same

$$\begin{aligned} L (dB) &= dBm (P_o) - dBm (P_{in}) \\ &= dB\mu (P_o) - dB\mu (P_{in}) \end{aligned}$$

ments and (2) optical time domain reflectometer (OTDR) measurements. The power meter technique requires a source of light that emits at the desired measurement wavelength and a power meter sensitive at that wavelength. Figure 2 shows a configuration, known as the cutback technique, for measuring attenuation with a combination of a light source and a power meter.

The cutback technique uses just one fiber for measurement but requires that an end piece of the fiber be cut off during the measurement process. First, the power emanating from the uncut fiber is measured; then the power from the cut fiber is measured. The dB/km loss factor is the difference in dB power measure-

**TABLE 2.
dBm TO mW
CONVERSION**

10mW = +10dBm	1 μ W = -30dBm
5mW = +7dBm	100nW = -40dBm
1mW = 0dBm	10nW = -50dBm
0.5mW = -3dBm	1nW = -60dBm
0.1mW = -10dBm	100pW = -70dBm
0.05mW = -13dBm	10pW = -80dBm
10 μ W = -20dBm	1pW = -90dBm
5 μ W = -23dBm	

**TABLE 3.
PHOTODIODE
WAVELENGTH RANGES**

Photodiode Type	Spectral Range
Silicon	400-1100nm
Germanium	800-1800nm
Indium Gallium Arsenide	900-1800nm
Mercury Cadmium Telluride	1000-1350nm

ments divided by the length of the cut-off piece of fiber. These measurements require that mode control techniques be employed for reproducible results, since each mode (or light path direction) within a multimode fiber produces a different attenuation. As recommended by the EIA in proposed Fiber Optic Test Procedure (FOTP) 50, for graded-index multimode fiber, a mode filter must produce an angular output distribution of light from a short fiber length that closely approximates that from a long test length, typically several kilometers. The relationship is shown in Figure 3. θ_S and θ_L are each defined by the angles at which the emitted light power drops to 10 % of peak. A variety of mode filters with the above characteristic has been produced; one, the serpentine bend mode filter, is shown in Figure 4.

Optical time domain reflectometers (OTDRs) are also capable of measuring fiber attenuation. As illustrated in Figure 5, an OTDR is a one-dimensional optical radar. A light pulse from the source is launched into the fiber, but the beamsplitter stops the initial laser light from reaching the

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The instrument provides smooth and continuous attenuation from 0 to 70dB with 0.01dB resolution. Calibrations are standard at 820, 850, 1300 and 1500nm. An on-board microcomputer allows the user to enter an

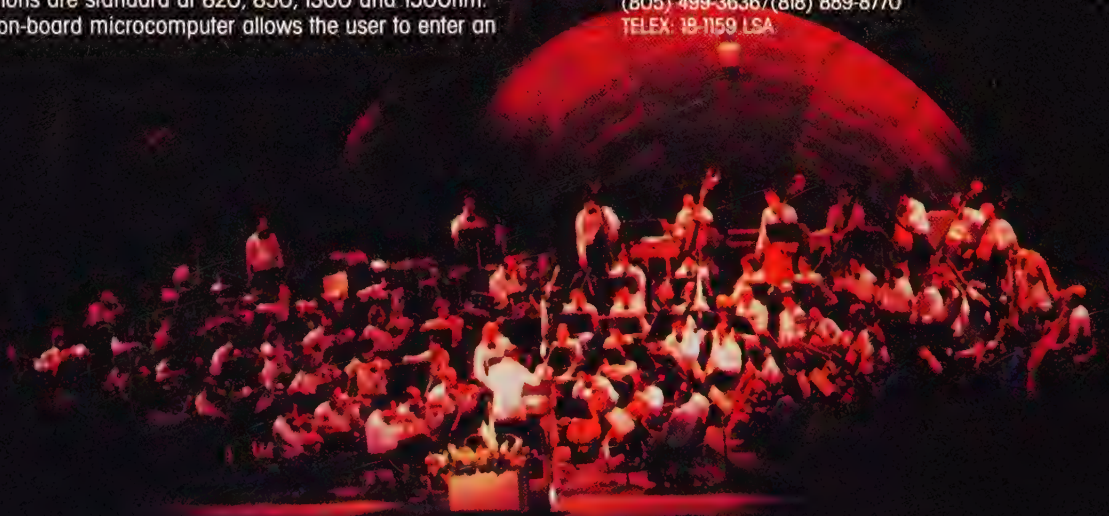
Auto-Scan program from the front panel.

Housed in a rack-mountable lab case the 1975XQ features user-friendly keypad, extra large LCD readout plus state-of-the-art design. Photodyne performance at your command.



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photodetector. This photodetector only records return signals (backscattered light).

Figure 6 shows an idealized plot of the signal display of an OTDR. The backscattered light return signal arises from two sources: (1) Fresnel reflections at fiber ends, breaks, and connectors, and (2) Rayleigh scattering from fiber inhomogeneity. The Rayleigh signal is a measure of fiber attenuation. The dB change per unit length of this signal measures fiber attenuation per length.

This measurement can be done by observing the backscattered signal on an oscilloscope; in some OTDRs, the measurement is done automatically with internal microcomputing electronics. The mode distribution in an OTDR measurement of fiber attenuation is not as precisely defined as in a power-meter measurement of attenuation, using a mode-control filter; thus these two measurements may not always correlate.

In time-domain measurements of fiber bandwidth, an optical power impulse from a pulsed laser source is sent down a fiber and the broadening of the pulse is measured at the output. The measured pulse broadening can be related to the -3dB frequency. For a Gaussian shape, $f_{-3dB} = 0.53/t_e$ is equal to the time for the pulse to broaden to $1/e$ down from the peak on both the leading and trailing edges. A typical measurement setup is shown in Figure 8.

Measuring transmission capacity

Bandwidth is related to the information-carrying capacity of an optical fiber and includes the various sources of signal distortion. Two techniques measure transmission capacity: (1) frequency domain measurements, and (2) time domain measurements. The baseband frequency response is measured directly in the frequency domain by determining the fiber response to a sinusoidally modulated light source. The EIA has proposed a standard frequency domain test setup for multimode fibers in FOTP-30. Figure 7 shows this test arrangement. The frequency is swept from DC to a high value such that the optical power roll-off can be observed in a long test fiber. The optical power at each frequency is normalized by measuring the power transmitted through a short reference length previously placed in the same test fixture. The -3dB bandwidth of a multimode optical fiber is defined as the lowest frequency at which the magnitude of the baseband frequency response in optical power has decreased by 3dB compared to zero frequency.

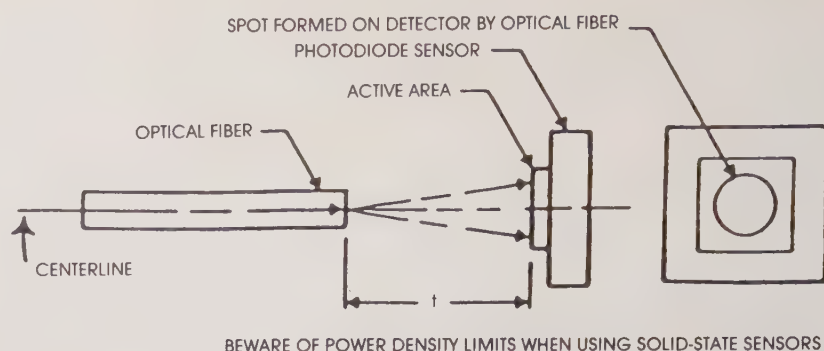


Figure 1.
Schematic of power density on detector.

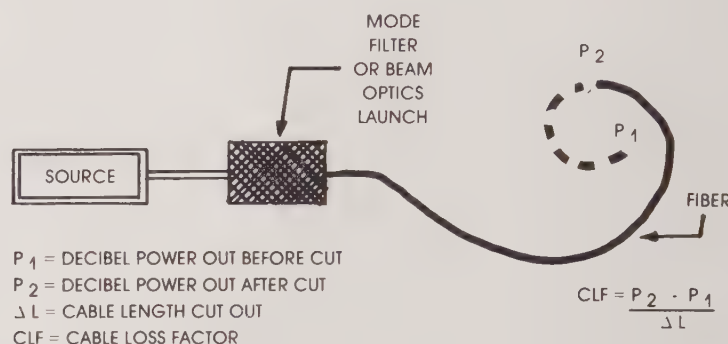


Figure 2.
Cutback technique for measuring attenuation.

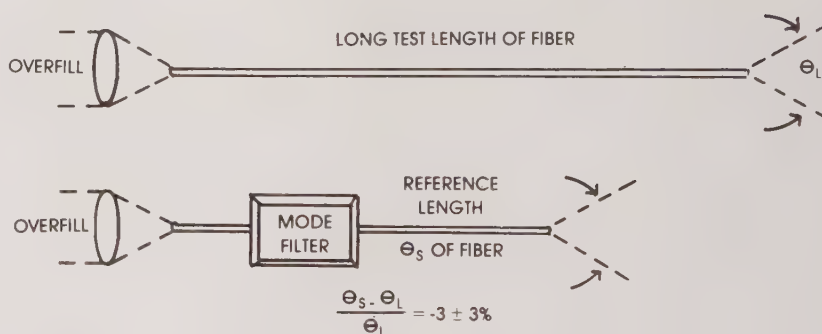


Figure 3.
Mode filter requirements.

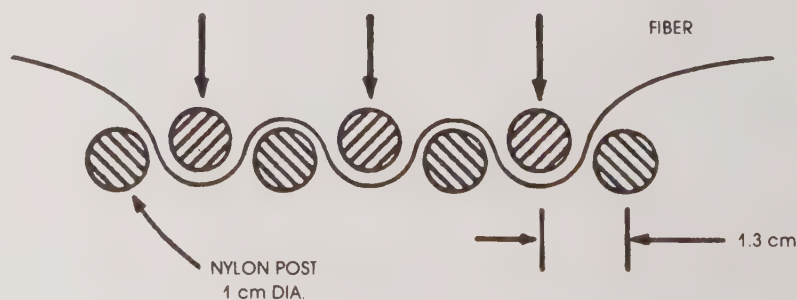


Figure 4.
Serpentine bend mode filter.

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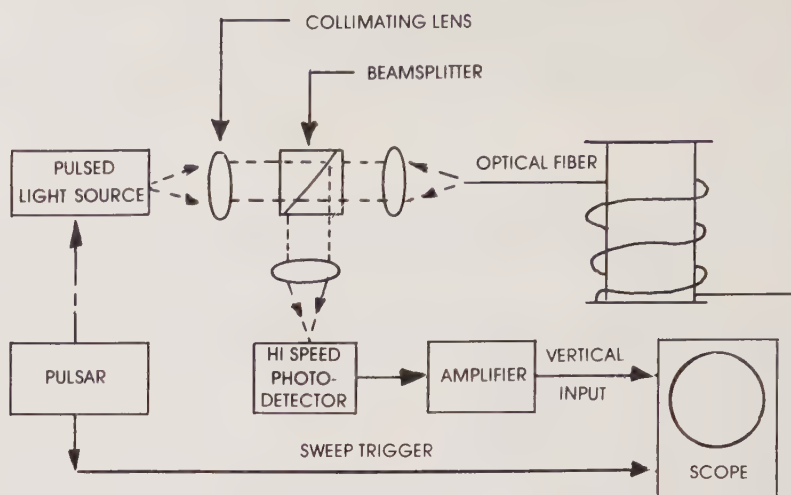


Figure 5.
The basic configuration of an OTDR.

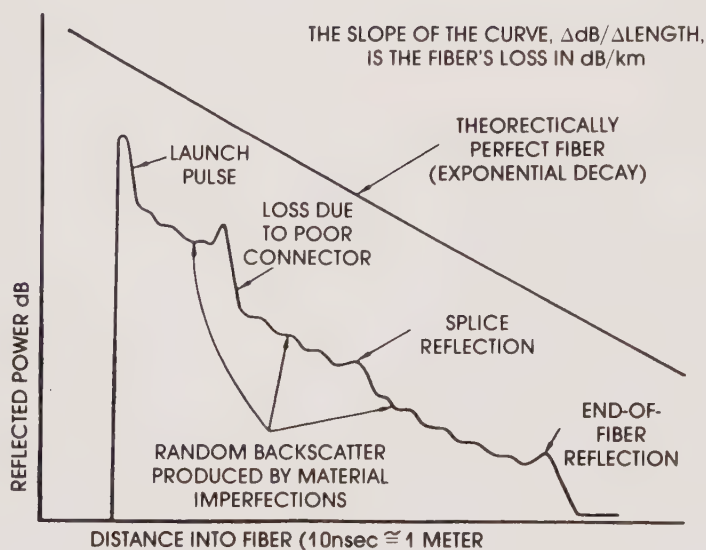


Figure 6.
An idealized plot of a backscatter signal from an OTDR.

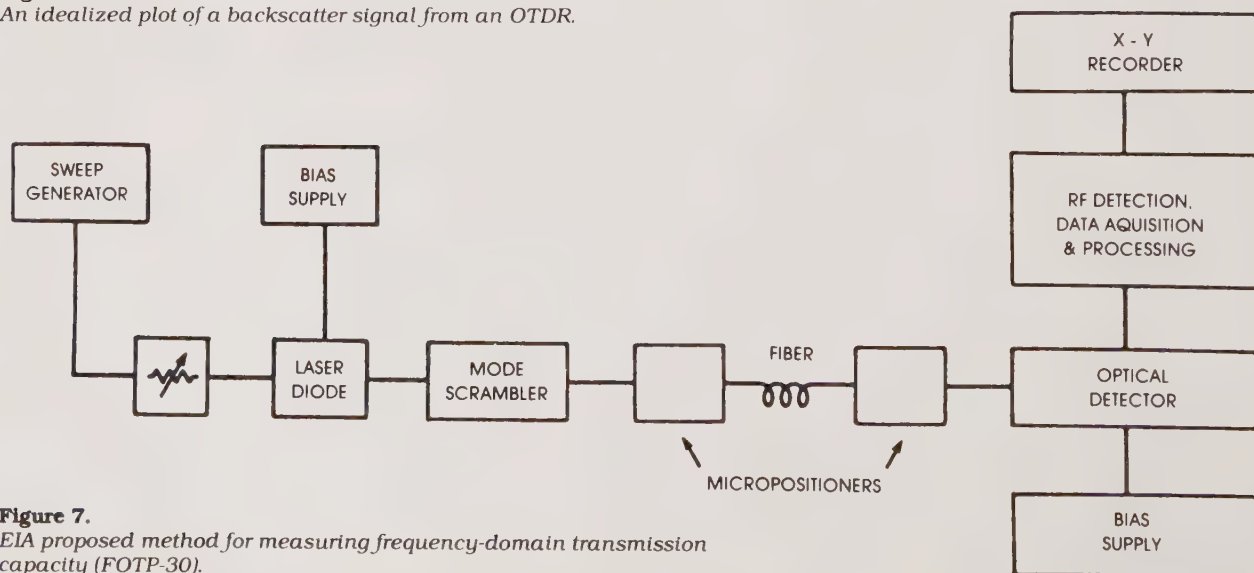


Figure 7.
EIA proposed method for measuring frequency-domain transmission capacity (FOTP-30).

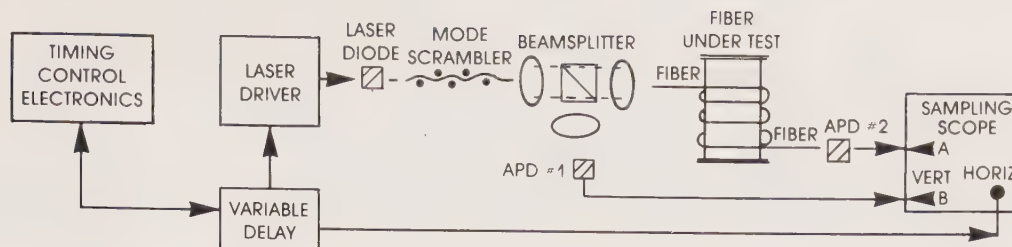


Figure 8.
Pulse dispersion measurement setup.

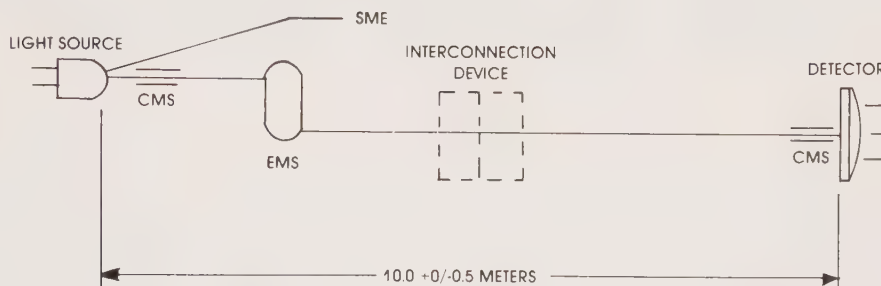


Figure 9.
EIA proposed method of measuring interconnect insertion loss (FOTP-34, Method B). SME=source monitor equipment. CMS=cladding mode stripper. EMS=equilibrium mode simulator.

Measuring interconnect attenuation

The insertion loss of fiber optic interconnecting devices, such as connectors, couplers, and splices, is an important system-design parameter. The measurement of insertion loss of these devices is covered by EIA proposed standard FOTP-34. Method B of this procedure is shown in Figure 9. The light transmitted by a test fiber shall first be monitored by a detector (P_0). Then the source power (P_{m1}) shall be monitored. The fiber is then cut and installation of a connector or splice is accomplished. The new detector power (P_1) is monitored, as well as the new source power (P_{m2}). Total insertion loss is calculated as follows:

$$\text{Loss (dB)} = 10 \log_{10} \left[\frac{P_1 \times P_{m2}}{P_2 \times P_{m1}} \right]$$

Paul H. Wendland
Photodyne Inc.

References

These measurement descriptions are necessarily brief because of space limitations. For more details regarding measurements in fiber optics, refer to the following:

1. E.I.A., Fiber Optic Test Procedures, 2001 Eye St. N.W., Washington, D.C. 20006.
2. N.B.S. Special Publication 637, Optical Fiber Characterization, US Dept. of Commerce, National Bureau of Standards, Washington, D.C. 20234.

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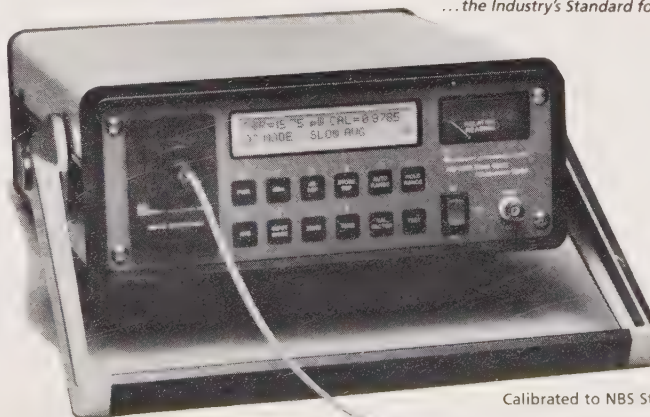
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Power Meter/Loss Test Sets

Company	Spectral Sensitivity (nm)	Absolute Power Measurement	Accuracy (absolute power)	Usable Range (dB attenuation)	Accuracy (loss measurement)	Temperature Coefficient (linearity)	Temperature Cos (zero offset/ noise floor)	Power Line (P) or Battery (B)?	Battery Life	Portable?	Weight	Price
Anritsu America Inc.	380-1800	+10-60dBm	±0.5 dB	70	±0.5 dB	—	—	P + B	20 hrs.	yes	10.5 oz.	—
	380-1800	+10-60dBm	±0.5 dB	70	±0.5 dB	—	—	P + B	8 hrs.	yes	5.9 lbs.	—
	380-1800	+10-90dBm	±0.5 dB	100	±0.5 dB	—	—	P + B	10 hrs.	yes	7.7 lbs.	—
Bowmar/ALI Inc. Instrument Div.	550-940	90dB	±0.2 dB	60	±0.2 dB	—	-80dBm	P + B	8-20 hrs.	yes	5 lbs.	\$4000
	200-600	70dB	±0.2 dB	40	±0.2 dB	—	-58dBm	P + B	8-20 hrs.	yes	5 lbs.	\$4000
Cossor Elec. Instruments Div.	850	—	—	49.9	±0.1 dB	—	—	P + B	8 hrs.	yes	3kg	2100* * pounds sterling
Equipements Scientifiques E-O Div.	400-1800	1pW-2mW	±0.5 %	90.3	±0.2 dB	—	—	P + B	16 hrs.	yes	2.4 kg	—
EG&G Gamma Scientific	200-1100, 800-1600	19.99 nW-1.99 mW	±1%	70	±0.3%	±0.5%	—	P	—	yes	4 lbs.	\$21,050-\$27,050
Fiberguide Instruments	400-1600	55dB	0.01 dB	55	0.01 dB	—	—	P	—	—	22 lbs.	\$8000 +
Fotec Inc.	600-900	+3-60dBm	±0.2 dB	source dependent	±0.05-0.2dB	0.1% °C	nil	P + B	200 hrs.	yes	8 oz.	\$625
	800-1800	+3-50dBm	±0.4 dB	source dependent	±0.5-0.2dB	0.1% °C	0.1nW °C	P + B	200 hrs.	yes	8 oz.	\$1100

Company	Spectral Sensitivity (nm)	Absolute Power Measurement	Accuracy (absolute power)	Usable Range (dB attenuation)	Accuracy (loss measurement)	Temperature Coefficient (linearity)	Temperature Cos (zero offset/noise floor)	Power Line (P) or Battery (B)?	Battery Life	Portable?	Weight	Price
Laser Precision Corp.	380-1800	9,999 mW	±3%	-90-+10	±0.15 dB	0°-45°C	-70dBm	P+B	6-8 hrs.	yes	11 lbs.	\$2750
Math Associates	820 (others avail.)	3 mW	1%	—	—	—	—	P+B	—	yes	—	\$375
Newport Corp.	400-1060	2 μ W-2W	—	—	±5%	—	—	B	300 hrs.	yes	2.5 lbs.	\$565
NKT (US) Inc.	850-900	0dBm	±0.5 dBm	55	±0.25 dB	stabilized	-80 dBm	P+B	15 hrs.	yes	11 lbs.	\$4000-5000
	1000-1600	0dBm	±0.5 dBm	40	±0.25 dB	stabilized	-65 dBm	P+B	15 hrs.	yes	11 lbs.	\$4000-5000
Perkins Research & Mfg.	800-1600	1mV/dBm	±2 dB	+3-40	±2 dB	0.1% °C	nil	B	100 hrs.	yes	1.25 kg	\$950
Photodyne Inc.	850-1800	-70-+3dBm	±5%	50	±0.5%	cooled to -20°C	1pW	P+B	10 hrs.	yes	12 lbs.	\$4750
Plantronics Wilcom	750-1800 (Ge), 800-1600 (InGaAsP)	0-65dB	0.2-0.5dB	30-45	±0.5 dB	2%	—	B	8-30 hrs.	yes	1-4.5 lbs.	\$460-4000
Stantel Components	850	—	—	50	±1 dB	+1dB -10°-+40°C	—	B	8 hrs.	yes	10.3 lbs.	—

Fiber Test Sources

Company	Source Type	Wavelengths Available (nm)	Output Power Adjustment Range (dBm or as specified)	CW or Pulsed?	Pulse Frequency	SM Compatible — Sizes	MM Compatible — Sizes	Stability (long-term: days, short-term: hours)	Power Line (P)/ Battery (B)	Temperature Range	Portable?	Weight	Price
Anritsu America Inc.	laser diode	1300, 1550	-6	CW	—	8-10/125 μ m	—	<0.2 dB days, <0.05 dB hrs.	P	0-40°C	yes	11 lbs.	—
	laser diode	850, 1300	—	CW	—	—	50/125 μ m	<0.2 dB days, <0.02 dB hrs.	P+B	0-40°C	yes	7.7-8.8 lbs.	—
	halogen lamp	600-1600	-45 (MM), -60 (SM)	CW	—	8-10/125 μ m	50/125 μ m	0.3 dB days, 0.3 dB hrs.	P	0-40°C	yes	15.4 lbs.	—
	HeNe laser	632.8	-8 (MM), -15 (SM)	CW	—	8-10/125 μ m	50/125 μ m	—	P	10-40°C	yes	8.8 lbs.	—

Company	Source Type	Wavelengths Available (nm)	Output Power Adjustment Range (dBm or as specified)	CW or Pulsed?	Pulse Frequency	SM Compatible — Sizes	MM Compatible — Sizes	Stability (long-term: days, short-term: hours)	Power Line (P)/ Battery (B)	Temperature Range	Portable?	Weight	Price
Anritsu (cont.) *plastic fiber: 1mm compatible	LED	850, 1300, 660*	-13, -20, -15*	CW	—	8-10/ 125 μ m	50/ 125 μ m	<0.1 dB days, <0.02 dB hrs.	P + B	0-40°C	yes	2.2-14.3 lbs.	—
Berkeley Nucleonics	laser diode	850	20dB	CW and pulsed	150 MHz	—	750/ 125 μ m	0.05% °C	P	10-40°C	yes	19 lbs.	\$8250
	LED	490, 560, 660, 820, 850	20dB	CW and pulsed	20 MHz	—	750 μ m	0.05% °C	P	10-40°C	yes	13 lbs.	\$2420-2950
Bowmar/ALI Inc. Instrument Div.	LED	850, 1300, 1550	-20-30	CW	—	8/ 125 μ m	50/ 125 μ m	—	P + B	—	yes	—	—
Equipements Scientifiques E-O Div.	laser	820, 1300	0.8-1.2mW	CW	—	—	50/ 125 μ m	$\pm$ 1% days, $\pm$ 0.5% hours	P + B	5-40°C	yes	2kg	—
Fotec Inc.	LED	665, 820, 850, 1300, 1550	100:1	CW	—	all	all	0.5dB days, 0.1dB hrs.	P + B	-10-40°C	yes	12 oz.	\$400-2200
Laser Precision Corp.	LED or laser	1300, 1500	1-10 μ W, 1.2-1 MW	CW and pulsed	30Hz-45MHz	8/ 125 μ m	—	—	P + B	0-45°C	yes	11 lbs.	\$8000
NKT (US) Inc.	LED or laser	850, 1300, 1500	25dB (internal)	pulsed (laser), CW + pulsed (LED)	1kHz	10/ 125 μ m	50/ 125 μ m	0.5dB days, 0.1dB hrs.	P + B	0-45°C	yes	11 lbs.	\$4000-13,000
Opto-Electronics Inc.	laser	820, 850, 1300, 1550	fixed	CW and pulsed	50MHz	all	all	—	P	0-60°C	yes	10 lbs.	\$4000+
Photodyne Inc.	LED	850, 1300	100:1	CW and pulsed	10MHz	—	50/ 125 μ m	$\pm$ 0.5dB (6 mos.), $\pm$ 0.5dB (1 wk.)	P	—	yes	8.5 lbs.	\$3500
Picosecond Pulse Labs Inc.	LED	820	fixed	pulsed	adjustable up to 10 MHz	—	all (SMA output connector)	—	P	—	yes	4 lbs.	\$985
Plantronics Wilcom	LED	850, 1300, 1550	10-15dB	CW	—	8-10/ 125 μ m	50-125, 100/140, 200/600 μ m	0.1dB days, 0.05dB hrs.	P + B	-10-40°C	yes	1-4.5 lbs.	\$435-1200
Quantronix Corp.	laser	1064, 1319	0-10W (average) (800kW peak)	pulsed	800Hz	all	—	—	—	—	—	—	—

Optical Time Domain Reflectometers (OTDRs)

Company	Wavelengths Available	Fiber Compatibility	Range to Detect Cleaved Fiber End	Range to Measure Backscatter Loss	Output to CRT? Recorder?	Power Line (P) or Battery (B)?	Portable?	Weight	Price
Anritsu America Inc.	850, 1300, 1500	SM, MM	72 Km	16-22.5 dB	both	P	yes	5.7 lbs.	—
Cossor Electronics Instruments Div.	850, 904, 1300	SM, MM	up to 60dB (one way)	up to 40dB (one way)	both	P + B	yes	8 kg	7000-15,000* *pounds sterling
Laser Precision Corp.	850, 1300	SM, MM	42dB (MM), 34dB (SM) (one way)	20dB (MM), 16dB (SM) (one way)	both	P + D	yes	25 lbs.	\$14,700-24,900
Opto-Electronics Inc.	820, 850, 1300, 1500	SM, MM	—	—	both	P	yes	15 lbs.	\$8000+
Orionics Inc.	1300	SM	27dB	6dB	both	P + B	yes	40 lbs.	\$23,300
	820, 1300	SM, MM	27dB	8dB	both	P + B	yes	25 lbs.	—
	820	MM	36dB	22dB	both	P + B	yes	40 lbs.	\$13,300
	1300	MM	28dB	10dB	both	P + B	yes	40 lbs.	\$19,900
Perkins Research & Mfg.	850, 904, 1300, 1550	SM, MM	85dB	20dB	CRT (rec. option)	P + B	yes	11.8 kg	\$15,000 (approx.)
Photodyne Inc.	850	MM	50dB	25dB	rec.	P + B	yes	24 lbs.	\$5850
Photon Kinetics Inc.	1300, 1550	SM	33dB (one way)	18dB (one way)	both	P	yes	35 lbs.	\$26,500-35,500
Stantel Components	850, 905, 1152, 1300	SM, MM	35-38 dB (MM), 48dB (SM)	15-20dB (MM), 17dB (SM)	both	P + B	yes	37 lbs.	\$14,750-19,500
Tektronix Inc.	820, 1300	MM	42.5dB	—	both	P + B	yes	36 lbs.	\$17,500-19,500

Field Tools for Fiber Splicing

Successfully splicing optical fibers in a telecommunications system revolves around factors of splice loss (transmitted power drop due to loss factors at the splice point, expressed in dB), splice longevity and reliability. Some thought should also be given to the potential difficulties of teaching the procedure to craftspeople who may be unfamiliar with fiber optics.

The most popular current method of joining optical fibers is fusion splicing. In this method, all buffer coating material is removed from approximately 4 to 6 cm of the fiber, using mechanical or chemical strippers, or both. Then the glass is cleaned of all foreign matter — freon degreaser on lens paper is a good cleaning agent. The fiber is cleaved (scored and broken) to provide as flat and perpendicular an end face as possible. Several very good available devices allow even a relatively inexperienced field technician to prepare acceptable cleaves with ease. For example, Fujikura, Sumitomo and Times Fiber offer excellent cleaving devices that are easy to maintain and relatively inexpensive.

The fibers then go into a mechanism that provides precise alignment along their longitudinal axes. Some fusion devices use X-Y-Z positioners, while others use precisely machined ceramic "V-blocks." The X-Y-Z positioners usually consist of micrometer translation stages; in some splicing units, one or more of them are motor-driven, and are controlled by pushbuttons or a four-position joystick. When ceramic blocks are used, X and Y alignment is achieved by placing the fibers in blocks. A micrometer stage is then used to position these fibers along the longitudinal axis.

Each approach has its merits, but V-blocks are generally easier to use, and provide exceptionally good fiber alignment if care is taken to keep them clean. As a final step, the fibers are butted in the field of a precisely controlled electric arc and melted together. (This is a simplified explanation of the fusion splice process: Each splicer manufacturer takes a slightly different approach.)

Aligning the fibers

The fibers may be held in the alignment apparatus by various means. Some splice units have magnetic clamping fixtures, some have

springloaded ones, and few use vacuum chucks. The magnetic and springloaded fixtures usually have soft rubber or similar material at the fiber contact points to prevent erroneous splice-loss readings stemming from microbending at the clamp. All clamping fixtures must be kept clean, but vacuum chucks especially may be prone to misalignment or clogging in a dusty environment.

The fusion splicing method has proven to be very effective in achieving field losses that average less than 0.2dB/splice. Among the manufacturers offering fusion splicers are Or-

the "loss budget" to handle such additional attenuation.

Protecting the splice

Whichever splice method is selected, there must be a means of protecting the joint after splicing. The bare glass exposed when buffer coatings are removed must be shielded against mechanical damage, and the fibers should be isolated from the stresses that may impinge on the adjacent cable. These stresses, induced by wind, thermal expansion and contraction, line construction, etc., can cause fiber breakage or micro-



The Valtec-designed splice organizer for loose tube fiber optic cable houses up to 12 fusion splices in duct, aerial or direct buried installations.

ionics, Power Technology, NKF, Fujikura, Anaconda and Siecor, as well as others. With the variety of instruments available, the user can usually find whatever combination of features he desires.

Another method rapidly gaining in popularity is the elastomeric splice sleeve manufactured by GTE. In this procedure, fibers are cleaned and cleaved in much the same way as in fusion splicing, but instead of being fused together, they are inserted into a precisely formed V-groove inside an elastomer sleeve. The centering forces of the elastomer provide excellent alignment of the fiber diameters, and the use of index-matching gel at the fiber end faces eliminates much of the reflection inherent in an unfused splice. These conditions, plus the tight tolerances held for core/cladding concentricity and centering by fiber manufacturers, ensures initial splice loss of typically 0.2dB average.

In a few cases, cable operating companies have opted to install SMA-type connectors at a splice point near the middle of the longer runs of cable. This practice provides an easily accessible test point. This type of splice, however, generally induces 2dB to 4dB of signal loss, and many long-haul systems do not have

bending-induced attenuation at the splice point. Microbending, or sharp curvatures with local displacements of a few micrometers, will cause significant radiative losses in optical waveguides.

The two most common methods of protecting the fiber splice utilize an epoxy-filled glass sleeve or an epoxy- or RTV-filled steel sleeve. In the glass-sleeve method, which Valtec advocates, the user removes 40 to 45cm of the loose primary tube from the fibers before splicing. He then positions a glass sleeve over the completed fusion splice, and injects a one-part ultraviolet curable epoxy into the sleeve. The final step is to cure the epoxy with a UV pencil lamp of the proper wavelength.

All of the materials at the splice — glass fiber, UV epoxy, and glass sleeve — are permanently bonded together, and all have similar thermal expansion characteristics. The entire assembly behaves identically during changes in temperature, thereby avoiding induced microbending loss or splice breakage due to temperature fluctuation.

In the steel-sleeve method, approximately 7 or 8cm of loose primary tube are removed. After fusion splicing the technician positions a steel sleeve over the splice and

crimps it onto the plastic tube on each side of the exposed splice point. The sleeve is then filled with RTV or two-part epoxy. This method has some disadvantages, the most important of which is that the thermal expansion and contraction of the sleeve can be transferred directly to the primary tubes and the splice. This may cause changes in attenuation and even splice breakage.

When elastomeric splices are used, the fibers and primary tubes may be prepared as described in either of the aforementioned methods. A glass tube over the elastomer sleeve provides protection for the bare glass at the splice point, and a plastic fixture can anchor the primary tubes, if desired.

Regardless of which method is used, a splice organizer (see photo) is needed to keep the fibers arranged in an orderly manner, free of kinks and tight bend radii. The organizer, which provides a tiedown or clamping mechanism to hold the cable firmly, thereby isolating the splices from the stresses on the cable, is re-entable in case of splice damage or the need to access the splice for testing or troubleshooting. Provisions for grounding and bonding metallic cable shielding and strength members are required in many cases, so most of the organizers have integral grounding ribbons or posts.

Whether fusion or mechanical splice procedures are used, the splice point must be protected from the elements. Water, wind, dirt, and rodent or insect invasion can adversely affect the fibers at the splice point. Where splices are placed in manholes or handholes, long-term immersion in water, sometimes with high concentrations of salt, is common. In aerial applications, the splice may be exposed to high winds and blowing dust or sand, and in ground- or pole-mounted pedestals insects and rodents often find convenient nesting sites.

To protect against these hazards, splice organizers are, in most cases, totally enclosed. Some organizers are designed to fit into any number of commercially available standard communications-industry splice enclosures. These are the same ones currently in use for protecting copper cable splices, and the tools for installing them are common. The enclosures may then be filled with a re-entable gel compound, pressurized with dry nitrogen, or left as is, depending on the environment and type of closure. (Valtec recommends that all manhole and direct buried splices be encapsulated to protect them from water.)

Other organizers are designed with an integral splice enclosure. Sometimes special tools may be required for their installation. In some instances, sealed injection boxes or pedestals may eliminate the need for a separate enclosure. Valtec, Anaconda and Siecor, among others, can supply splice organizers for in-field use. For splices in cable vaults or other indoor locations, enclosures are not necessarily required.

Terminating the cable

In many cases the fiber cable may be routed directly to the central office equipment rack. At this point the cable may be "fanned out," or jumper cables (pigtails) can be spliced on, so that individual fibers can be routed to their respective transmit or receive equipment. With fan-out kits, the individual fibers can be routed up to four meters from the cable end without splicing. This is accomplished by inserting the primary fiber tubes into a sleeve of protective fiberglass and installing the appropriate connector directly to the cable fiber. This is a particularly attractive method when system attenuation is critical.

When longer pigtailing is required, special rack-mounted splice or-

ganizers are used. These are designed to fit into the standard central-office equipment racks, and pigtails of any length can be spliced to the cable fibers at this point. This system allows the use of any type of equipment connector, some of which are not easily installed on site. The decision on the type lies in the hands of the equipment manufacturer, but the most popular is the grind-and-polish SMA type, which is easily installed with epoxy in the field.

Fiber attenuation equals optical power input (in dBm) minus power output (in dBm). Power input is determined by connecting an optical power meter to the laser diode through a short fiber pigtail, usually less than two meters. Small portable optical power meters are available from Laser Precision, Photodyne, EG&G, Bowmar/ALI and others.

Bandwidth measurement can be done with a swept frequency technique. A sweep oscillator modulates the output of the laser diode from 0-200MHz with a sweep oscillator. This output, coupled into the fiber under test, is detected at the output end with a photodiode, where it is amplified and fed into spectrum analyzer.

W.F. "Skip" Toney
Valtec Corp.



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Fiber Coupling Loss Nomograph

The nomograph provides a means of making worst-case estimates of the coupling loss in a butt joint, from which the power coupled into a fiber may be calculated. All you need is specifications commonly available on manufacturers' data sheets for diodes and fibers.

Engineering assumptions are that all specified power is emitted from the front of the diode where the butt is made, and that the diode is perfectly butted to the fiber, leaving only an infinitesimal air gap. The nomograph also assumes the use of step-index fiber: with dimensionally similar graded-index fiber, the power loss will be about 1 decibel greater than the nomograph indicates.

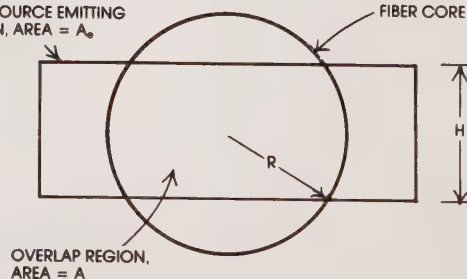
With the nomograph you can compute tradeoffs in a fiber system: i.e., numerical aperture vs. fiber core diameter, in order to find the optimum fiber from the standpoint of coupling loss.

Given specifications from the data sheets of an optical fiber and light-emitting or laser diode, plus the area (A) of overlap between the emitting area (A_e) and the fiber core, coupling loss is estimated by putting a straight-edge across this nomograph.

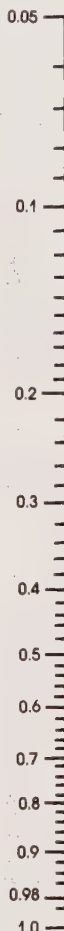
You must find the portion of the light source's active emitting area that actually butts up against the fiber to use the nomograph. The emitter is often rectangular; if it is longer than the fiber's diameter, overlap area (A) must be calculated by plane geometry.

LIGHT SOURCE EMITTING REGION, AREA = A_e

FIBER CORE

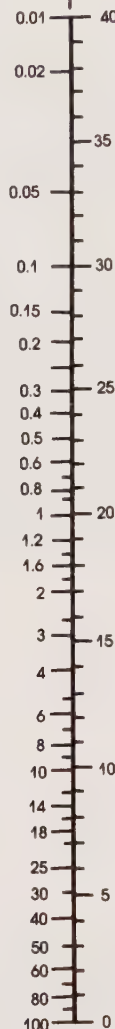


NUMERICAL APERTURE (NA) OF FIBER



RATIO OF COUPLED POWER TO EMITTED POWER

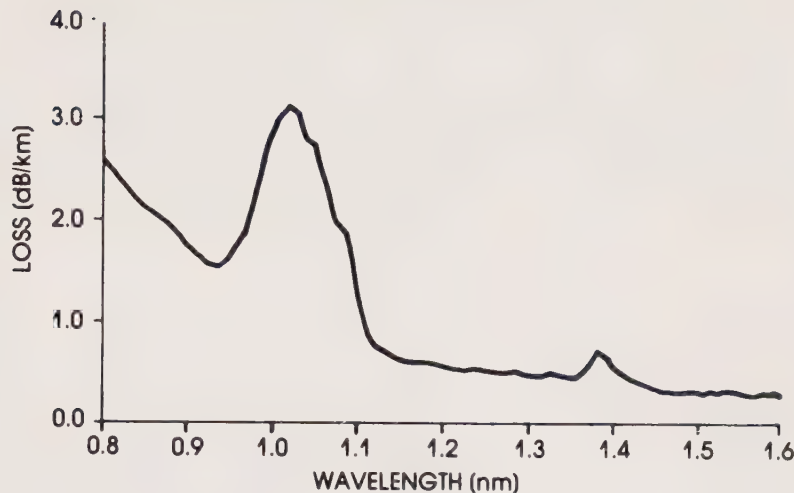
$\frac{P_c}{P_e} \times 100$ $10 \log \frac{P_c}{P_e}$



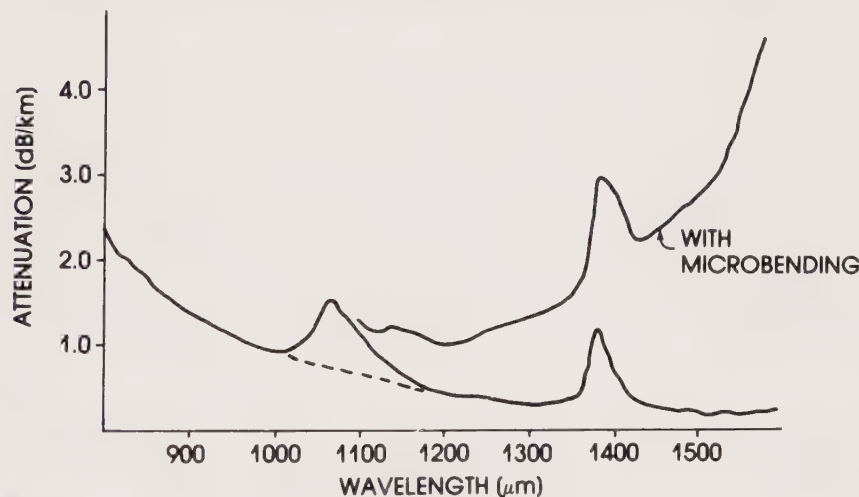
RATIO OF OVERLAP AREA TO EMITTING AREA (A/A_e) $\times 100$



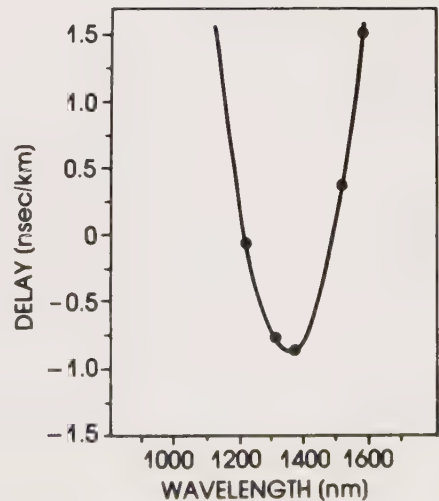
Typical Single-Mode Fiber
Spectral Attenuation



Microbending Effect on Attenuation



Time Delay
for Unshifted
(1300nm)
Type Fiber



SOURCE: CORNING GLASS WORKS

Fiber Optic Connectors

MANUFACTURERS' INFORMATION ON SIGNIFICANT CONNECTOR PARAMETERS

Company	Type	Single/Multimode	Field Installable?	Housing Material	Ferrule Material	Fiber Sizes (Core/OD or OD only)	No. of Fibers	Nominal Attenuation First Use (dB)	1000 Matings/Dematings	Termination Method	Applications	Comments
Amp Inc.	DMP	M	yes	plastic	plastic	125-1040 μ m	1, 2, multiple	1-2	same	full crimp	automotive, photocopiers	
	FSMA	M	yes	stainless steel	stainless steel	from 125-1040 μ m	1, 2, multiple	1-2	same	bond, crimp	harsh military, industrial environments	
	Optimate	M	yes	metal	plastic		1, 2			bond, crimp	telecom, datacom	
Amphenol Bendix Connector Div.	epoxy-polish	M	yes	aluminum or stainless steel	stainless steel	50/125 μ m, 100/140 μ m	multiple	<1.5	after 500: <0.2 change	grind, polish	military, rugged commercial	also for bundled fibers; hybrid fiber/electrical connector available
	expanded beam lens	M	yes	aluminum or stainless steel	plastic (lens)	50/125 μ m, 100/140 μ m	multiple	<1.5	after 500: <0.2 change	strip, cleave	military, rugged commercial	also available in hermetically sealed version; other environmental options
Amphenol N. America Div.	804	M	yes	plastic	plastic	from 250 μ m-1mm	1	1.75	change =0.2	epoxy, polish	datacom, process control	
	905,906	M	yes	aluminum brass or stainless steel	aluminum, brass or stainless steel	from 125 μ m-1mm	1	0.8 typ	change =0.2	epoxy, polish	telecom, datacom, defense avionics	
	rec-tangular (PCB type)	M	yes	aluminum	stainless steel, brass or combination	from 125 μ m-1mm	up to 8	0.8-1.1	change =0.2	epoxy, polish	PC boards	
	circular shell	M	yes	aluminum	stainless steel, brass or combination	from 125 μ m-1mm	up to 8	0.8-1.1	change =0.2	epoxy, polish	harsh military, industrial environments	
Anaconda Lightwave	SMA	M	yes	immers.-tinned brass	immersion-tinned brass	125 μ m or 140 μ m	1	0.4	after 200: 0.7	grind, polish	telecom, datacom, video	
AT&T Technologies	Biconic 1006A	M	yes	polycarbonate	thermoset plastic	125 μ m	1	0.7 typ	same	polish	telecom	available mounted on 50/125 and 62.5/125 fibered cable
	Biconic 1005B	M	yes	polycarbonate	thermoset plastic	125 μ m	1	0.8 typ	same	polish	datacom	available mounted on 50/125 and 62.5/125 fibered cable

Company	Type	Single/Multimode	Field Installable?	Housing Material	Ferrule Material	Fiber Sizes (Core/OD or OD only)	No. of Fibers	Nominal Attenuation First Use (dB)	1000 Matings/ Dematings	Termination Method	Applications	Comments
Augat Fiberoptics	SMA 698-DSC	M	yes	nickel- plated brass	nickel- plated brass	50/125 μ m- 200/230 μ m (and custom)	1	0.8- 1.4		grind, polish	short-haul, datacom	Amphenol 905 intermatable
	SMA 698-JSC	M	yes	nickel- plated brass	nickel- plated brass	50/125 μ m- 200/230 μ m (and custom)	1	0.8- 1.4		grind, polish	short-haul, datacom	Amphenol 906 intermatable
Automatic Connector	SMA FS Series	M	yes	stainless steel	brass or aluminum	200 μ m and up (and custom)	1	<1		epoxy, crimp, grind, polish	datacom	
	4000 series	M	yes	polycar- bonate	epoxy	50/125 μ m, 100/140 μ m (and custom)	1	<1		epoxy, crimp, grind, polish	datacom, telecom	AT&T Technologies intermatable
	4000 series ACI	M	yes	anodized aluminum	epoxy	50/125 μ m, 100/140 μ m (and custom)	1	<1		epoxy, crimp, grind, polish	datacom, telecom	AT&T Technologies mating method
	4000 series AT&T-style blind mate	M	yes	polycar- bonate	epoxy	50/125 μ m, 100/140 μ m (and custom)	1	<1		epoxy, crimp, grind, polish	datacom, telecom	PC board-type fixture
	4000 series ACI-style blind mate	M	yes	anodized aluminum	epoxy	50/125 μ m, 100/140 μ m (and custom)	1	<1		epoxy, crimp, grind, polish	datacom, telecom	PC board-type fixture
Belling Lee Intec (UK)	SMA	M	yes	brass	nickel- silver	200- 600 μ m	1	<1.75		crimp, cleave	military, datacom, CCTV	Amphenol- compatible
Breech-Lok Prod. G&H Tech. Div.	SMA	S	yes	beryllium- copper	beryllium- copper	125 μ m, 140 μ m	1	1	same	crimp, cleave	military, LAN	
	single- and multi- channel	S	yes	aluminum	beryllium- copper	125 μ m, 140 μ m	single, multi up to 19	1	same	crimp, cleave	military, LAN	
CLTO (France)	4032C single- channel					50/125 μ m	1	2	after 500: <0.2 change			
	4034 SMA		yes			100/140 μ m		2		cleave	military, industrial	
Deutsch Industrial Prods. Div.	3000 Series expanded beam lens duplex	M	yes	plastic	—	50/125 μ m- 100/140 μ m	2	1.5 typ	after 500: same	cleave	datacom, telecom	
	3000 Series rack-and- panel expanded beam lens	M	yes	stainless steel	—	50/125 μ m- 100/140 μ m	1	1.5 typ	after 500: same	cleave	datacom, telecom	
	3000 Series in-line SMA expanded beam lens	M	yes	metal	—	50/125 μ m- 100/140 μ m	1	1.5 typ	after 500: same	cleave	datacom, telecom	

Company	Type	Single/Multimode	Field Installable?	Housing Material	Ferrule Material	Fiber Sizes (Core/OD or OD only)	No. of Fibers	Nominal Attenuation First Use (dB)	1000 Matings/ Dematings	Termination Method	Applications	Comments
Deutsch (Continued)	3000 Series SMA expanded beam lens	M	yes	metal	—	50/125 μ m- 100/140 μ m	1	1.5 typ	after '500: same	cleave	datacom, telecom	
Dorran Photonics	Biconic	S	no	plastic	silica- filled plastic	125 μ m, 140 μ m	1	0.4		epoxy, cleave, grind	telecom, medical, LAN	high-strength plastic in housing
		M	yes	plastic	silica- filled plastic	125 μ m, 140 μ m	1	0.4		epoxy, cleave grind	telecom, medical, LAN	
Fort (France)	Optican SMA	M	yes	stainless steel	stainless steel	50/125 μ m, 100/140 μ m, 200/280 μ m	1	<1.5	after 250: <2	grind, polish	datacom	
Fort Fiber Optics	SMA	M	yes	nickel- plated bronze	nickel- plated bronze	50/125 μ m- 200/280 μ m	1 or 2	<1	after 500: <2	crimp, cleave/ grind, polish	industrial, datacom	
Fujikura Ltd. (Japan)	FFC plug and adaptor	M	yes	stainless steel	ceramic	125 μ m	1	<1		polish	telecom, datacom	NTT compatible
	FFC plug and adaptor	S	no	stainless steel	ceramic	125 μ m	1	<1		polish	telecom, datacom	NTT compatible
General Fiber Optics	SMA	M	yes	stainless steel or aluminum	stainless steel or aluminum	50 μ m- 1000 μ m	1 (or custom)	<2- <4	same	epoxy typ	high-power telecom, special	many different fiber types and sizes available
	530 AMP-type	M	yes	plastic	plastic	50 μ m- 600 μ m	1 (or custom)	<2- <6		epoxy, grind, polish	illumination, short-haul data link	
	High- power	M		usually aluminum	reflective lining	50 μ m- 1200 μ m	1 (or custom)			coupler	high-power lasers	custom laser-to- fiber-optic interface
	Low- power	M		stainless steel	—	100 μ m- 1200 μ m	1 (or custom)	5-7% Fresnel		direct mount	low-power laser beam distribution	
GTE Fiber Optics	expanded beam lens	M	yes	polymer	—	variable	1	1.0 typ	same	cleave	telecom, military, datacom, medical	
	expanded beam lens	S	yes	polymer	—	variable	1	1.0 typ	same	cleave	telecom, military, datacom, medical	
Hellerman Deutsch (UK)	OSMA	M	yes	electroless nickel- plated brass	nickel- silver	200 μ m- 1mm core	1	2		grind, polish	telecom, military, datacom	Amphenol 905 compatible
	TC2	M	yes	aluminum alloy	nickel- silver	50/125 μ m- 1mm	1	1 typ		cleave, grind, polish	telecom, military, datacom	
	MC2	M	yes	aluminum alloy	nickel- silver	50/125 μ m- 1mm	2- 12	1.5 typ		cleave, grind, polish	telecom, military, datacom	opto-electrical option
	"Wipe- clean"	M	yes	aluminum- bronze alloy	nickel- silver	200 μ m- 1mm	1-10	2 typ		grind, polish	military, datacom	
	FRR	M	yes	aluminum alloy	brass	fiber bundle	3-31			grind, polish	military, datacom	based on PATT 602 connector
	RR	M	yes	aluminum alloy	brass	100 μ m- 600 μ m	3-31				telecom, military, datacom	based on PATT 602 connector
Hewlett-Packard OC Div.	HP- style	M	yes	brass	brass	100/140 μ m	1	1.5	same	grind, polish	datacom	

Company	Type	Single/Multimode	Field Installable?	Housing Material	Ferrule Material	Fiber Sizes (Core/OD or OD only)	No. of Fibers	Nominal Attenuation First Use (dB)	1000 Matings/ Dematings	Termination Method	Applications	Comments
Hitachi Cable America	FA-type compati- ble	M	yes	metal		50/125 μ m, 85/150 μ m	1				telecom, datacom	
	Hitachi standard	M	yes	plastic		50/125 μ m, 85/150 μ m	1				telecom, datacom	
Holtek Optronics (Sweden)	Biconic	M	yes	stainless steel/ brass	stainless steel/ brass	50/125 μ m, 100/140 μ m	1	0.8	1.0	grind, polish	datacom	
Hughes Aircraft Connecting Devices Div.	PC-mount	M	yes	aluminum	brass- stainless steel	all	2-32	1.2- 1.7		grind, polish	military	
	Herm- aphro- ditic	M	yes	aluminum	brass- stainless steel	all	1-8	1.2- 1.7		grind, polish	military tactical	
	rack-and- panel rec- tangular	M	yes	diallyl phthlate or aluminum	brass- stainless steel	all	20- 212	1.2- 1.7	same	grind, polish	military airborne test	
	MIL- C-28876 circular	M	yes	aluminum	brass- stainless steel	all	2-8			grind, polish	military shipboard, airborne	
Interoptics	GFS-24/A SMA, GFS-25/A SMA	M	yes	steel	tungsten	50/125 μ m- 400/440 μ m	1	<1	same	cleave, grind, polish	voice and datacom	
	GFS-13A SMA	M	yes	steel	tungsten	50/125 μ m- 400/440 μ m	1	<0.5	same	cleave, grind, polish	voice and datacom	
	GFS-3	M	yes	steel	tungsten	50/125 μ m- 400/440 μ m	1	<0.6	same	cleave, grind, polish	voice and datacom	
	MMS-3	S	yes	steel	tungsten	4/80 μ m, 8/125 μ m	1	1(max)	same	cleave, grind, polish	voice and datacom	
	MMS-3/KP	S	no	steel	tungsten	4/80 μ m, 8/125 μ m	1	<0.5	same		voice and datacom	pigtail
	EMS-3 rack-and- panel	S	no	steel	tungsten	4/80 μ m, 8/125 μ m	1	<1	same		voice and datacom	
ITT Cannon Microminiature & FO Prods.	SMA-RF	S	yes	stainless steel	stainless steel	50 μ m- 150 μ m	1	1.2- 2	after 500: same	epoxy, grind, polish	datacom	ITT proprietary jewel align- ment system
	FOMC	S	yes	aluminum	stainless steel	50 μ m- 150 μ m	2-8	1.2- 2	after 500: same	epoxy, grind, polish	military communica- tions	see above
	plastic- housed dual- channel	S	yes	plastic	stainless steel	50 μ m- 150 μ m	full duplex	1.2- 2	after 500: same	epoxy, grind, polish	computer systems	see above
	MIL- C-38999 contact system	S	yes	aluminum	stainless steel	50 μ m- 150 μ m	multiple	1.2- 2	after 500: same	epoxy, grind, polish	avionic and naval commu- nications	see above
	rack-and- panel- mount contact system	S	yes	aluminum	stainless steel	50 μ m- 150 μ m	multiple			epoxy, grind, polish	avionic and naval commu- nications	see above; for FO retrofit into digital commu- nications systems
JBM Swiss Screw	FO bundle	M		stainless steel or nickel- plated brass	stainless steel/ plastic or rubber		bundle			epoxy, grind, polish	industrial borescopes, medical il- lumination, detectors	

Company	Type	Single/Multimode	Field Installable?	Housing Material	Ferrule Material	Fiber Sizes (Core/OD or OD only)	No. of Fibers	Nominal Attenuation First Use (dB)	1000 Matings/ Dematings	Termination Method	Applications	Comments
NEC Electronics	D4 P/N OD 9470	M	yes	stainless steel	stainless steel	50/125 μ m- 100/150 μ m	1	<0.7	same	ferrule trimming, polish	telecom, datacom	available with autoplug, multi- plug and other housings
	D4 P/N PD 9474	S	yes	stainless steel	stainless steel	10/125 μ m	1	<1	same	ferrule trimming, polish	telecom, datacom	available with alternative housings
	D3 P/N OD 9374	S	yes	stainless steel	stainless steel	10/125 μ m	1	<1	same	ferrule trimming, polish	telecom, datacom	compatible with NTT connector specification
	D3 P/N OD 9373	M	yes	stainless steel	stainless steel	50/125 μ m, 80/125 μ m	1	<0.7	same	ferrule trimming, polish	telecom, datacom	compatible with NTT connector specification
	FC P/N OD 9370	M	yes	stainless steel	stainless steel	50/125 μ m, 80/125 μ m	1	<0.7	same	ferrule trimming, polish	telecom, datacom	compatible with NTT connector specification
	FC P/N OD 9371	S	yes	stainless steel	stainless steel	10/125 μ m	1	<1	same	ferrule trimming, polish	telecom, datacom	compatible with NTT connector specification
	plastic P/N OD 9478 snap-on	M	yes	plastic	plastic	50/125 μ m- 200/250 μ m	1	<1	same	polish	telecom, datacom	
Newport Corp.	SMA	M	yes	nickel- plated brass	aluminum	50/125 μ m- 200 μ m	1	<1.5		grind, polish	telecom, datacom	
OFTI	SMA 906	M	yes	nickel- plated brass or aluminum	stainless steel, ceramic, alu- minum or zinc die cast	85 μ m- 1140 μ m	1	0.5- 2 typ	0.3 change	crimp, epoxy/ no epoxy, polish	datacom, military tele- com, process control, medical	
	SMA 906	S	yes	nickel- plated brass or aluminum	ceramic	85 μ m- 1140 μ m	1	1	same	crimp, epoxy, polish	datacom, military tele- com, process control, medical	
	SMA 905	M	yes	nickel- plated brass or aluminum	stainless steel, ceramic, aluminum or zinc die cast	125 μ m- 1900 μ m	1	0.5- 2	0.3 change	crimp, epoxy/ no epoxy, polish	datacom, military tele- com, process control, medical	
	CFC AMP Optimate inter- matable	M	yes	aluminum	aluminum	85 μ m- 1900 μ m	1	<2	same	crimp, epoxy, polish	datacom, military tele- com, process control, medical	
Optronics Ltd. (UK)	SMA	M	yes	stainless steel	stainless steel	50/125 μ m- 100/140 μ m	1	<2	<4	grind, polish	short-haul communica- tions	
	SMA	M	yes	stainless steel	stainless steel	50/125 μ m- 200/250 μ m	1	1.5	2.5	cleave	short-haul communica- tions	
	SMA	S	yes	stainless steel	stainless steel	7/125 μ m	1	<0.25	<1	grind, polish	long-haul communica- tions	
Seiko Inst. & Elec.	FC-type NTT standard	S	yes	metal alloy	SAS 316F and ceramic capillary	9/125 μ m	1	<1	same	grind, polish	telecom	
	FC NTT standard	M	yes	metal alloy	SAS 316F and ceramic capillary	50/125 μ m, 80/125 μ m	1	<0.4	same	grind, polish	telecom	

Company	Type	Single/Multimode	Field Installable?	Housing Material	Ferrule Material	Fiber Sizes (Core/OD or OD only)	No. of Fibers	Nominal Attenuation First Use (dB)	1000 Matings/ Dematings	Termination Method	Applications	Comments
Siecor		M	yes	metal	metal/ glass capillary	50/125 μ m, 100/140 μ m	1	for 50 μ m:1	for 50 μ m: same	epoxy, grind, polish	short-haul datacom	
Stantel Components	Leeds	M	yes	stainless steel	stainless steel, jeweled ferrule	70 μ m- 260 μ m	1	1		cleave, grind, polish	telecom, military	
	SMA	M	yes	stainless steel	stainless steel, jeweled ferrule	70 μ m- 260 μ m	1	1		cleave, grind, polish	telecom, military	
	Stratos	M	yes	stainless steel	stainless steel, jeweled ferrule	70 μ m- 260 μ m	1	1		cleave, grind, polish	telecom, military	
Sumitomo Elec. USA	mini-BNC	M	yes	metal	metal	50/125 μ m- 62.5/125 μ m		0.5	0.5 typ	grind, polish	optical patch panel or cross- connect panel for telecom, datacom	
		S	yes	metal	metal	8/125 μ m						pigtail
Switchcraft	SMA	M	yes	brass/ stainless steel	brass	125 μ m- 600 μ m	1	1.4- 1.7	1.8- 2.2	cleave and UV-cured adhesive	short-haul datacom	
TRW Connector/ FO Products	Optalign	M	yes	anodized aluminum	—	to 230 μ m	1	0.3	after 500: 1.5	cleave and scribe, guide with index- matching oil	telecom, datacom, military	
	Optalign	S	yes	anodized aluminum	—	to 230 μ m	1	<0.5	after 500: 2	cleave and scribe, guide with index- matching oil	telecom, datacom, military	
Thomas & Betts Optoelectronic Prods.	FSMA	M	yes	metal	metal	125 μ m- 200 μ m	1	1.5 typ	same	cleave in ferrule	datacom	

Optical Fiber and Cable

Fiber, Single-Mode

COMPANY	TRANSMISSION WAVELENGTH RANGE (nm)	CUT-OFF WAVELENGTH (nm)	ATTENUATION (dB/km)	MODE FIELD DIAMETER (μ m)	ZERO DISPERSION WAVELENGTH (nm)	ESTIMATED SPlice LOSS (dB)	MAXIMUM DISPERSION (psec/km; λ)	CORE DIAMETER (μ m)	CORE-TO-CLAD OFFSET (μ m)	PROOF STRENGTH (kpsi)	OUTSIDE DIAMETER (μ m)	TOLERANCE ($\pm$ μ m)	MAXIMUM CONTINUOUS LENGTH (km)
Acome Paris, France	1300-1550	—	0.5/ 0.7	8-10	—	0.2	—	8	1-2	50	125	3	2.5
AT&T	1310-1550	1330	0.4/ 0.35	8.7 ± 0.7	1310 ± 10	0.05	3.2; 1285-1300 17; 1550	8.3	1	50	125	2.5	—
BICC	1330-1550	1175 ± 75	0.4/ 0.2	50 ± 5	1300- 1550	0.1	3.5; 1285-1330	8	<1	—	125	3	6.4
BIW Cable Systems Inc.	1300-1550	1130- 1270	0.7	10	1310 ± 20	—	3.5; 1285-1300	8.7 ± 1.3	1	50	250	15	—
Cabioptric S.A.	1275-1325	1200	0.5	10	1315	0.20	4	8	0.5	70	125	1	4.5
Celwave Systems Inc.	1285-1330 1525-1575	1130- 1270	0.4, 0.5, 0.6, 0.7	9-11	1300	<0.2	≤ 3.5 ; 1285-1330	8.7	≤ 1	50	250	15	2.2
Corning Glass Works	1300	1130- 1270	≤ 0.4 or ≤ 0.5	9-11	1300	—	≤ 3.5 ; 1285-1330	8.7	≤ 1	50	125	3	12.6
	1550	1130- 1270	0.22 or 0.27	—	1550	—	2.5; 1525-1575	—	—	50	125	—	12.6
Diaguide, Inc.	850	750-800	5.0	—	1300	0.3-1.	—	6	2	90	125	3	2.0
	488	450	30	—	—	—	—	4	3	90	125	3	2.0
	630	600	10	—	—	—	—	6	3	90	125	3	2.0
EOTec Corp.	630	63	12	—	—	—	—	4	1	—	80 or 125	3	6
	820	820	3	—	—	—	—	5	1	50	80 or 125	3	6
	630	600	18	—	—	—	—	3.5	1	50	80 or 125	3	6
	850	820	3.5	—	—	—	—	5	1	50	80 or 125	3	6
Fibronics Ltd.	1300-1550	1200 ± 70	0.5	10	1315 ± 15	—	3.5; 1285-1330	—	—	50	125	—	2-3
Furukawa Electric America Inc. New York, NY	1285-1330	1100- 1280	0.4	10 $\pm$ 1	1310 ± 20	<0.2	3.5; 1285-1330	9	0.5-1	50	125	3	10.0
GEC Optical Fibres Ltd. London, England	1300	1100- 1250	0.4-1.1	5 $\pm$ 0.5	1305	—	6; 1275-1325	8	1	50	250	15	12
ISPRA Fiberoptics Industries Herzlia	1300	1200 ± 70	0.45	9-11	1280- 1320	—	3.5; 1290-1330	9	>1	50	125-250	3, 15	2.2
ITT-Electro Optical Products	1300	1200 ± 70	0.5-1	10 $\pm$ 1	1310	0.15	<3.5; 1285-1330	10 $\pm$ 1	—	50	125	3	5
Northern Telecom	1300-1550	1220 ± 90	0.4- 0.7	10 $\pm$ 1	1310 ± 10	0.15	3; 1285-1330	8-10	1	50	125	3	6
Olex Cables	800-1600	1160	≤ 0.6	10.2	1300	0.2	18	8	0.1	80	125	3	5
Optical Cable	1300	1130- 1270	0.5	9-11	—	—	3.5	8.7	1	—	125	3	6
Pirelli Cable Corp.	1300	1130- 1270	0.4- 1	10	—	—	<3.5; 1285-1330	—	<1	50	125	3	6.4
Remee Products	1300	1130- 1270	0.5-0.9	9-11	—	—	3.5; 1285-1330	8.7	<1	50	125	3	5

COMPANY	TRANSMISSION WAVELENGTH RANGE (nm)	CUT-OFF WAVELENGTH (nm)	ATTENUATION (dB/km)	MODE FIELD DIAMETER (μm)	ZERO DISPERSION WAVELENGTH (nm)	ESTIMATED SPLICING LOSS (dB)	MAXIMUM DISPERSION (pssec/km; λ)	CORE DIAMETER (μm)	CORE-TO-CLAD OFFSET (μm)	PROOF STRENGTH (kpsi)	OUTSIDE DIAMETER (μm)	TOLERANCE ($\pm\mu\text{m}$)	MAXIMUM CONTINUOUS LENGTH (km)
Siecor Corp.	1300	1130-1270	0.4-0.7	10	1290-1330	0.05	≤ 3.5 ; 1295-1325	8.7	≤ 1	50	125	3	6
SpecTran Corp.	1300-1550	1200	0.5/0.3	10	1310	0.06	3.5; 1300	9	1	50-100	125	3	5.3
Standard Wire & Cable Co.	1300-1550	1100-1280	0.5	10 $\pm$ 1	1300	0.01	1285-1330	10 $\pm$ 1	± 4	60	125	3	6
Sumitomo Electric Research Triangle	1310-1550	1100-1270/1100-1300	0.4-0.8/0.35-0.7	10	1310	0.07	3.5-5.0; 1285-1330	9	≤ 1	70	125	3	CF

CF = Consult Factory

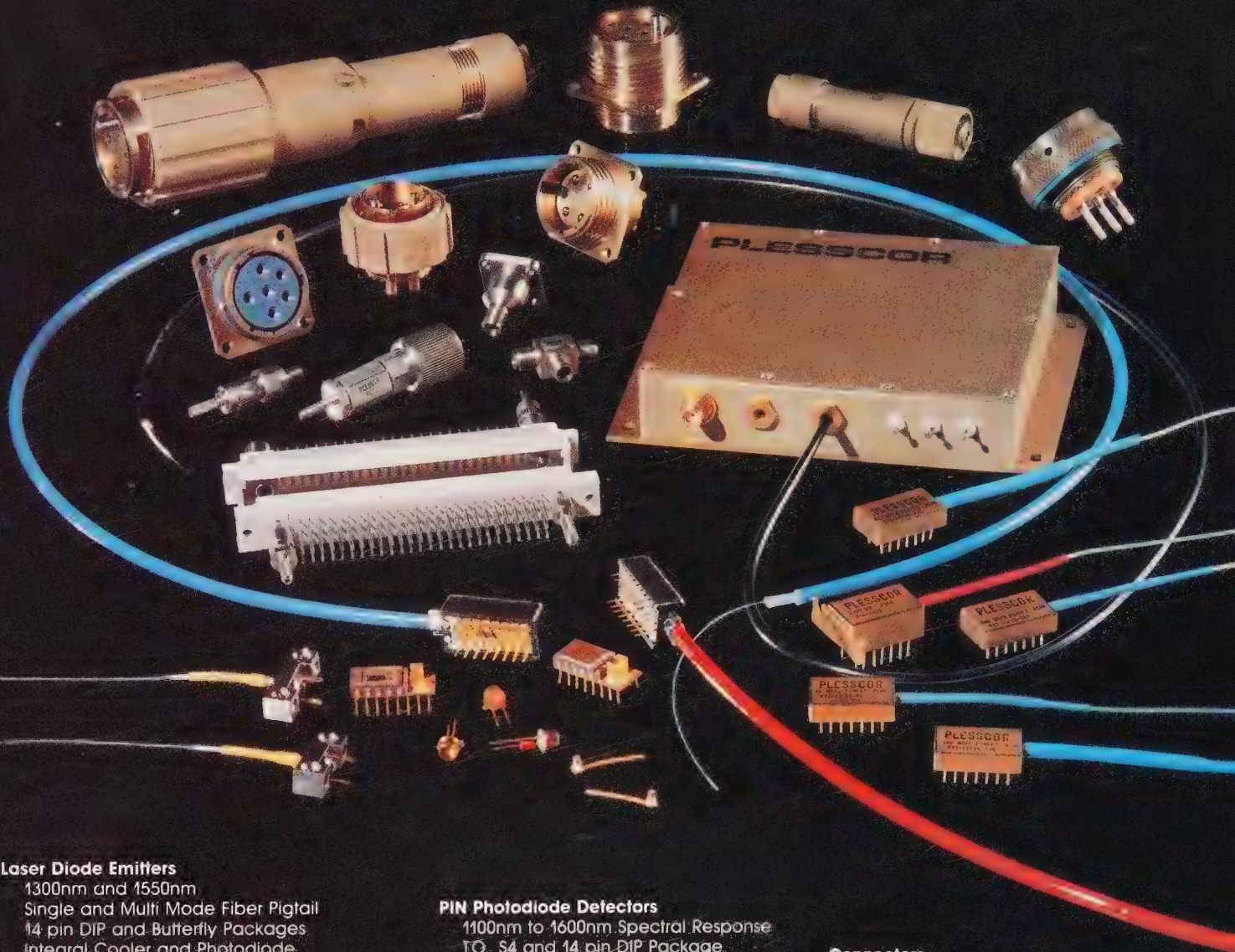
Fiber, Multimode

COMPANY	TRANSMISSION WAVELENGTH RANGE (nm)	ATTENUATION (dB/km)	NUMERICAL APERTURE	BANDWIDTH (MHz-km)	ESTIMATED SPLICING LOSS (dB)	MAXIMUM DISPERSION (pssec/km; WAVELENGTH RANGE)	CORE DIAMETER (μm)	CORE NONCIRCULARITY (μm)	CORE-TO-CLAD OFFSET (μm)	PROOF STRENGTH (kpsi)	OUTSIDE DIAMETER (μm)	TOLERANCE ($\pm\mu\text{m}$)	MAXIMUM CONTINUOUS LENGTH (km)
Acome Paris, France	850-1300	3-1.2	0.2	200-750	0.2	<6; 1300	50 $\pm$ 3	± 3	≤ 3	50	125	3	2.5
AT&T Technologies	825-1300	3.50-1.20	0.23	300-1100	0.2	300-1100; 825 300-1100; 1300	50 $\pm$ 6	—	—	50	125	2.5	—
BICC	850-900 1275-1325	1.3 0.7 3 $\geq$ 2.4	0.20 $\pm$ 0.015	1500-400	0.1-0.2	< 6; 1300	50 $\pm$ 3	$\pm 6\%$	> 6%	0.5%	125-250	3	2.2
BIW Cable Systems Inc.	850-1300	3.5-6	0.20-0.29	200-1000	—	—	50	—	—	70	250 or 500	15	2.1
	850-1300	3.5-6	0.29	100-500	—	—	100	—	—	100	500	15	2.1
Cabloptic S.A.	1200-1600	0.8	0.21	1000	0.15	—	50	1	0.8	70	125	1	4.5
Celwave Systems	820-870 1285-1330	2.4-3	0.20	400-1300	0.25	—	50	2.5	≤ 3	50	250	15	2.2
Cordon et Equipements	850-1300	0.7-3	0.2-0.4	10-1200	0.2	0.3	50,85, 100,200	± 3	125,140, 280,380	45,57	250,500, 600	30	2.5
Corning Glass Works	850& 1300	3.2-4 1.2-2	0.260 $\pm$ 0.015	100-200 300-800	—	—	85	± 3	≤ 3	50-100	125	± 3	2.2
	850& 1300	2.4-3 0.6-1	0.20 $\pm$ 0.015	600-1300 600-1500	—	—	50	—	≤ 3	50-100	125	± 3	2.2
	850& 1300	2.4-2.7 0.8-1.2	0.20 $\pm$ 0.015	400-600	—	—	50	—	≤ 3	50-100	125	± 3	2.2
	850& 1300	4-5 3-4	0.29 $\pm$ 0.015	100-300	—	—	100 $\pm$ 4	—	—	50-100	140 $\pm$ 6	—	2.2
Diaguide, Inc.	850	3	0.2	25	0.1-0.3	—	50 $\pm$ 3	1.5	1	—	125	3	10
	850	3	0.2	25	0.1-0.3	—	60 $\pm$ 3	1.8	1.2	—	150	3	8
	850	5	0.2	25	0.1-0.3	—	100 $\pm$ 10	3	2	—	150	3	2.8
	850	10	0.2	20	0.1-0.3	—	200 $\pm$ 10	6	6	—	250	12	2
	850	10	0.2	20	0.1-0.3	—	400 $\pm$ 20	12	12	—	500	25	0.5
	850	10	0.2	20	0.1-0.3	—	600 $\pm$ 30	18	18	—	750	38	0.22
	850	10	0.2	20	0.1-0.3	—	800 $\pm$ 40	24	24	—	1000	50	0.12
	850	10	0.2	20	0.1-0.3	—	1000 $\pm$ 50	30	30	—	1250	60	0.08
	660	20	0.39	—	—	—	200	6	12	—	400	—	10
	660	20	0.39	—	—	—	400	12	24	—	500	—	2.5
	660	20	0.39	—	—	—	600	18	36	—	750	—	1
	660	20	0.39	—	—	—	800	24	48	—	1000	—	0.6
	660	20	0.39	—	—	—	1000	30	60	—	1250	—	0.4
Ensign-Bickford	850	6	0.37	17	—	—	110	—	3	100	125	5	2.2
	850	6	0.37	17	—	—	120	—	4	100	140	5	2.2
	850	6	0.37	17	—	—	200	—	6	100	230	0-10	2.2
	850	6	0.37	13	—	—	400	—	7	50	430	0-10	1.1
	850	6	0.37	9	—	—	600	—	9	50	630	10	0.5
	850	6	0.37	—	—	—	1000	—	10	50	1035	10	0.1
Hard-clad radiation-resistant fiber	850	12	0.37	17	—	—	110	—	3	100	125	5	2.2
	850*	12	0.37	17	—	—	120	—	4	100	140	5	2.2
	850*	12	0.37	17	—	—	200	—	6	100	230	0-10	2.2

COMPANY	TRANSMISSION WAVELENGTH RANGE (nm)	ATTENUATION (dB/km)	NUMERICAL APERTURE	BANDWIDTH (MHz-km)	ESTIMATED SPICE LOSS (dB)	MAXIMUM DISPERSION (psec/km; WAVELENGTH RANGE)	CORE DIAMETER (μ m)	CORE NONCIRCULARITY (μ m)	CORE-TO-CLAD OFFSET (μ m)	PROOF STRENGTH (kpsi)	OUTSIDE DIAMETER (μ m)	TOLERANCE ($\pm \mu$ m)	MAXIMUM CONTINUOUS LENGTH (km)
Ensign-Bickford (cont.)	850*	12	0.37	13	—	—	400	—	7	50	430	0-10	1.1
	850*	12	0.37	9	—	—	600	—	9	50	630	10	0.5
	850*	12	0.37	—	—	—	1000	—	10	50	1035	10	0.1
EOTec Corp.	820	6	0.4	25	—	—	200	—	—	—	—	—	—
	850	6	0.29	100	—	—	100	—	—	—	—	—	—
Fibronics Ltd.	850-1300	4, 2	0.2	400	—	—	50	—	—	100	125	—	2
	850-1300	—	0.2-0.29	200-400	—	—	50-100	—	—	50-100	125-140	—	2
	850	5	0.3	20	—	—	200	—	—	—	600	—	1
	850-1300	—	—	200-400	—	—	50-100	—	—	50-100	125-140	—	2
	850-1300	—	0.2-0.29	200-400	—	—	50-100	—	—	50-100	125-140	—	2
Filotex Draveil, France	800-900	10	0.20	7.5	0.5	150	100	4	4	50	140	5	0.005
Furukawa Electric America Inc. New York, N.Y.	1285-1330	0.7-1.0	0.21	400-1200	<0.1	—	50	<6%	<7	50	125	3	10
GEC Optical Fibres Ltd. London, England	1300	0.7-2	0.21	1200- 1500	—	880	50	3	3	50	250	15	9
Huber & Suhner	850	10	0.4	10	0.4	—	200	—	8	45	600	48	2.5
ISKRA Yugoslavia	850	10	0.3	20	0.3	—	200	—	—	57	380	20	1.1
	1300	<1	0.2-0.02	>800	0.1	200; 1300	50	3	3	57	125	3	2.2
	850	<2.8	0.20 $\pm$ 0.02	>500	0.1	400; 850	50	<3	<3	57	125	3	2.2
ISPRA Fiberoptics Industries	850	3	0.20	800	—	—	50	>3	>1	50	125-250	4-15	2.2
	1300	1	0.20	1200	—	—	50	>3	>1	50	125-250	4-15	2.2
	850	3.5	0.29	500	—	—	100	>5	>1	50	140-300	4-15	2.2
	1300	1.5	0.29	700	—	—	100	>5	>1	50	140-300	4-15	2.2
ITT Electro-Optics	850	3-4	0.235 $\pm$ 0.015	200-800	0.2	—	50	—	—	50	125	3	5
Le Verre Fluore France	500-4500	1	0.12	—	—	—	70	—	35	50	250	20	0.1
Northern Telecom	840-1300	2.5-4	0.20	>500	0.15	1	50	$\pm$ 3	3	50	125	3	3
Olex Cables	800-1600	$\leq$ 1	0.20 $\pm$ 0.02	$\geq$ 800	0.2, 0.4	500; 1300	50	0.8	0.6	80	125	3	2.5
Optical Cable	850-1300	2.5-4/ 1-2	0.2	200-800/ 200-3000	—	—	50	—	—	—	125	—	2
	850-1300	3.5-5/ 1.75-2.5	0.29	100-400/ 100-500	—	—	62.5	—	—	—	125	—	2
	850-1300	3.5-5/ 1.75-2.5	0.29	100-400/ 100-500	—	—	100	—	—	—	140	—	2
	850	7	—	17	—	—	200	—	—	—	230	—	2
Pirelli Cable Corp.	850-1300	3-5/ 1-2	0.20	200-1000	—	—	50	>0.95	$\leq$ 3	50 or 100	125	3	2.2
Poly-Optical Products Santa Ana, CA	450-850	900-1500	0.53-0.58	—	—	—	68- 6350	—	—	—	75-6500	$\pm$ 10%	>100k (ft.)
Raycom Systems	670-820	6	0.35	20	0.1	—	200	—	—	200	230	—	2
Remee Products	800-1300	1-6	0.2-0.4	1200	—	—	50-200	—	—	100	250/500	—	2.2
Scholly FiberOptic	380-900	105	0.47 $\pm$ 0.03	—	6-9%	—	250, 500, 750, 1000, 1500, 2000	—	—	—	5	$\pm$ 5%	15
Schott Glaswerke	400-2000	20-0.6	0.08-0.3	2000	—	—	25-600	$\pm$ 1	$\pm$ 2	>200	60-1000	$\pm$ 2	12
Siecor Corp.	1300	0.9-2	0.20	400-1200	0.30	—	50	—	$\leq$ 1	50	125	$\pm$ 3	6
SpecTran Corp.	180-1000	<10	0.24 $\pm$ 0.02	20	—	—	105, 200, 320	4%	3	50 or 100	125, 140, 200	3	2.2
	850-1300	<5	0.29 $\pm$ 0.02	100-1500	—	-2.5; 1300	62.5, 100, 125	4%	3	50 or 100	125, 240, 385	5	2.2
Standard Wire & Cable Co.	850-1300	2.4-3.4	0.20-0.24	200	0.25	800-1100	50 $\pm$ 3	$\pm$ 1	$\pm$ 3	60	125	$\pm$ 3	6
U.I. Lapp KG	800-900	8.0-10	0.4	10	—	—	200	$\pm$ 8	380	45	600	$\pm$ 48	2.5

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Cable

COMPANY	NO. OF FIBERS	SINGLE-MODE	MULTIMODE	PULL STRENGTH (Newtons)	STRENGTH MEMBER MATERIAL	SHEATH MATERIAL	LOOSE	TIGHT	BOTH	CABLE DIA.	TELECOM	MILITARY	DATA/COM	INDUSTRIAL	PRICE (\$/km)
Acome Paris, France	1-210	●	●	Various	FRP or steel	PE	●	—	—	3.1mm- 30mm	●	●	●	●	CF
American Fiber Technologies	1-100	●	●	2000- 6000	Kevlar or Steel	—	—	—	LT open channel	—	●	●	●	●	CF
AMP Inc. Harrisburg, PA	1	—	50/125	150	Kevlar	TPE	—	●	—	3mm	P	P	P	P	\$900
	1	—	85/125	150	Kevlar	TPE	—	●	—	3mm	P	P	P	P	\$1350
	1	—	100/140	150	Kevlar	TPE	—	●	—	3mm	P	P	P	P	\$1290
	2	—	50/125	300	Kevlar	TPE	—	●	—	3.0 x 6.1mm	P	P	P	P	\$1700
	2	—	85/125	300	Kevlar	TPE	—	●	—	3.0 x 6.1mm	P	P	P	P	\$2480
	2	—	100/140	300	Kevlar	TPE	—	●	—	3.0 x 6.1mm	P	P	P	P	\$2360
	2	—	50/125	300	Kevlar	TPE	—	●	—	3.8 x 7.7mm	D,P	D,P	D,P	D,P	\$1870
	2	—	85/125	300	Kevlar	TPE	—	●	—	3.8 x 7.7mm	D,P	D,P	D,P	D,P	\$2730
	2	—	100/140	300	Kevlar	TPE	—	●	—	3.8 x 7.7mm	D,P	D,P	D,P	D,P	\$2600
	2	—	50/125	200	Kevlar	Fluorocarbon	—	●	—	3.1 x 5.6mm	D,P	D,P	D,P	D,P	\$3250
	2	—	85/125	200	Kevlar	Fluorocarbon	—	●	—	3.1 x 5.6mm	D,P	D,P	D,P	D,P	\$4200
	2	—	100/140	200	Kevlar	Fluorocarbon	—	●	—	3.1 x 5.6mm	D,P	D,P	D,P	D,P	\$4000
	1	—	980/1000	10-12 kg.	—	Polyethylene	—	—	—	2.2mm	P	P	P	P	\$1100
	1	—	980/1000	10-12kg.	—	Polyethylene	—	—	—	2.2mm	P	P	P	P	CF
	2	—	50/125	100	LCP	PVC	—	●	—	1.16" x .075"	●	●	●	●	\$4100
	2	—	63/125	100	LCP	PVC	—	●	—	1.16" x .075"	●	●	●	●	\$5740
	2	—	85/125	100	LCP	PVC	—	●	—	1.16" x .075"	●	●	●	●	\$4920
	2	—	100/140	100	LCP	PVC	—	●	—	1.16" x .075"	●	●	●	●	\$5740
	2	—	485/500	100	Polyester	PVC	—	●	—	1.16" x .075"	●	●	●	●	\$4920
AT&T	4-144	●	●	2670	Fiberglass or Steel	High Density Polyethylene	●	—	—	0.50"	DB, D,O	DB, D,O	DB, D,O	DB, D,O	CF
Berkenhoff & Drebes GmbH	1	—	●	500	Aramid	PUR/ PVC/PE	●	—	—	4.0mm	—	—	P, D	P, D	\$1200
	2	—	●	3000	Aramid & FRP	PE	●	—	—	8.5mm	—	—	D,DB	D,DB	\$3000
	2	—	●	500	Aramid	PUR/ PVC/PE	●	—	—	4 x 6.5mm	—	—	D,P	D,P	\$2300
	8	—	●	3000	Aramid & FRP	PE	●	—	—	5.5 x 9.5mm 12.5mm	—	—	D,DB	D,DB	CF
Berk-Tek Inc.	1-50	●	●	Various	Metal, Fiberglass, Aramid fiber	TPE/ Copolymer/ PVC/PE	—	—	●	Variable	—	DB, D,O, P	DB, D,O, P	DB, D,O, P	CF
BICC	Up to 200	●	●	Various	Metallic & nonmetallic	Polyethylene/ PVC/Plenum	—	—	●	Various	DB, D,P	DB, D,P	DB, D,O, P	DB, D,O, P	CF
BIW Cable	1-48	●	●	450-2700	Steel or Dielectric	Polyolefin & fluoropolymers	—	—	●	.125"- .650"	●	●	●	●	CF
Brand-Rex Co.	1-12	—	●	—	Kevlar, Fiberglass, Steel	—	—	—	●	2mm- 15mm	—	D,O	DB, D,O, P	DB, D,O, P	CF
Cabloptic SA	Up to 10	●	●	—	—	—	—	—	—	—	●	—	●	●	CF
Celwave Systems	Up to 24	●	●	2700	Glass rein- forced plastic	PUR/ PVC/PE	—	—	●	≤16.0mm	DB, D,O	DB, D,O	DB, D,O	DB, D,O	CF
Cordons et Equipment	1-70	—	—	100 per equipped	Kevlar	PVC/ PE	—	—	●	3.8mm- 31mm	DB, D,O, P	DB, D,O, P	DB, D,O, P	DB, D,O, P	CF
Key: DB = direct burial; D = duct; O = overhead; P = plenum CF=Consult Factory															

COMPANY	NO. OF FIBERS	SINGLE-MODE	MULTIMODE	PULL STRENGTH (Newtons)	STRENGTH MEMBER MATERIAL	SEATH MATERIAL	LOOSE	TIGHT	BOTH	CABLE DIA.	TELECOM	MILITARY	DATACOM	INDUSTRIAL	PRICE (\$/km)
Chromatic Technology	1-24	—	●	As required	Steel/Dielectric	Chromatek	—	—	●	.20-1.5"	DB, D	DB, D	DB, D	DB, D	CF
	1-24	—	●	500-3000	Aramid fiber	Chromatek	—	—	●	.12-1.0"	—	—	D,P	D,P	CF
	1-48	—	●	As required	Steel/Dielectric	Chromatek	—	—	●	.20-2.0"	DB, D,O	—	—	—	CF
	1-24	—	●	As required	Steel/Dielectric	Chromatek	—	—	●	.20-2.0"	—	D,O	D,O	D,O	CF
EOTec Corp.	1	—	●	400	Kevlar	PVC	—	●	—	3.0mm	—	—	DB,D	DB,D	CF
	1	—	●	400	Kevlar	PVC	—	●	—	3.0mm	—	—	DB,D	DB,D	CF
	1	—	●	400	Kevlar	PVC	—	●	—	3.0mm	—	—	DB,D	DB,D	CF
	2	—	●	600	Kevlar	PVC	—	●	—	3.0 x 6.7mm	—	—	DB, D	DB, D	CF
	1	—	●	400	Kevlar	PVC	—	●	—	3.0mm	—	—	DB,D	DB, D	CF
	1	—	●	400	Kevlar	PVC	—	●	—	3.0mm	—	—	DB,D	DB, D	CF
	2	—	●	600	Kevlar	PVC	—	●	—	3.0 x 6.7mm	—	—	DB, D	DB, D	CF
Fibronics Ltd.	2	—	●	1000	Kevlar	PVR	—	●	—	—	—	●	—	—	CF
	Up to 24	●	●	1500	Steel/Glass	PVC	—	—	—	—	—	—	D	D	CF
	1, 2	—	●	500	Kevlar	PVC	—	—	—	—	—	—	●	—	CF
	Up to 12	—	●	1500	Kevlar	PVC	—	—	—	—	—	—	D	D	CF
	2 or 4	—	●	1000	Kevlar	Halar	—	—	—	4.8mm	—	—	P	—	CF
Filotex Draveil, France	1	—	—	500	Glass	ETFE/PFA	—	●	—	1.8mm max	—	●	—	●	CF
	1	—	—	400	Glass	Polyimide	—	●	—	1.60mm max	—	●	—	●	CF
Focom Systems	2-8	—	—	—	Kevlar	Polytene	—	—	—	8mm	●	●	●	●	\$150
Furukawa Electric America New York, N.Y.	4-96	●	●	3000 max.	Steel/FRP	ALST/PE	—	●	—	10-20 mm	DB, D,P	—	—	—	CF
Huber & Suhner	1-20	—	●	Approx. 200 per fiber	Kevlar	PVC/PE/PU	—	—	●	Various	—	—	—	●	CF
ITT	4-72	●	●	2700	Steel/Fiberglass	PE	●	—	—	.35-.79"	DB, D,O	—	DB, D,O	DB, D,O	CF
	*Slotted core	1-18	●	1700	Steel	PE	●	—	—	.37-.54"	D	D	D	D	CF
	18-48	●	●	2700	Steel, Fiberglass	PE	●	—	—	.5-.7"	DB, D,O	—	—	—	CF
	2-4	—	●	1800	Kevlar	PU	—	●	—	.2-.3"	—	D	—	—	CF
	2	—	●	600	—	PU	—	●	—	.24 x .12"	—	—	D	—	CF
	1	●	●	300	Kevlar	PU	—	●	—	.12"	—	—	D	—	CF
NKT (US)	Up to 12	●	●	400,000	Steel	PE/Lead/PE	●	—	—	110mm	●	●	●	●	CF
Northern Telecom	96	●	●	2700	Steel, Fiberglass	Steel/poly	—	—	—	13-22	DB, D,O	DB, D,O	DB, D,O	DB, D,O	CF
Olex Cables	1-60	●	●	300-2500	FRP	PE/PVC/Nylon	—	●	—	3-25mm	DB, D	O, D	DB, D,O	DB, D,O	CF
Olin Brass East Alton, IL	1-8	●	●	220-5000	Copper Alloy	Copper Alloy	—	—	●	.024"-.200"	DB, D,O	●	—	DB, D,O	\$.90-\$5.00/m
Optelectron	1-2	—	●	0.5	—	—	—	—	—	2.2&2	●	●	●	●	\$450/km
Optical Cable	1 or 2	●	●	300	Aramid	PVC	—	—	—	3mm	D, P	—	D, P	D, P	CF
	2-60	●	●	2000	Aramid	PVC	—	—	—	—	DB, D	DB, D	DB, D	DB, D	CF
	2-24	●	●	1500	Glass/Epoxy	PE	●	—	—	7.5-14mm	D, O, D, O, D, O, D, O, P	—	O, P	—	CF
	2-24	●	●	1500	Glass/Epoxy	PE	●	—	—	7.5-14mm	DB, D	—	DB, D	—	CF
Phalo/DCC	1-48	●	●	>400 lbs.	LCP	PE/PVC/TFE	—	●	—	Various	●	●	●	●	\$.50-\$2.00/meter
Phillips Cable Ltd.	4-80	●	●	50 x OD	Dielectric Stainless Steel	PE	●	—	—	12mm-35mm	DB, D, O	—	—	DB, D, O	CF
Philips Kommunikations	Various	●	●	2500	Glass fiber/Kevlar	PE	●	—	—	12-20mm	D	DB, D	D	D, O	CF
Pirelli Cable	1	●	●	500	Kevlar	PVC/PU	—	—	●	3mm	—	—	O, D	O, D	CF
	2	●	●	1000	Kevlar	PVC/PU	—	—	●	3mm x 6.3mm	—	—	D, O	D, O	CF

COMPANY	NO. OF FIBERS	SINGLE-MODE	MULTIMODE	PULL STRENGTH (Newtons)	STRENGTH MEMBER MATERIAL	THEAT MATERIAL	LOOSE	TIGHT	BOTH	CABLE DIA.	TELECOM	MILITARY	DATACOM	INDUSTRIAL	PRICE (\$/km)
Pirelli Cable (cont.)	1-5	•	•	345	Kevlar	Fluoro- polymer	—	•	—	2.5- 7.8	P	P	P	P	CF
	4-180	•	•	2700	Steel/ Kevlar	PE	—	—	•	8mm- 20mm	DB, D, O	DB, D, O	DB, D, O	DB, D, O	CF
Raycom Systems	1	—	•	600	Kevlar	PVC	•	—	—	3mm	—	•	•	•	\$1475
Remee Products	Up to 24	•	•	Up to 3000	Metallic/ dielectric	PVC/ PU/PE	—	—	•	—	—	•	•	•	CF
Scholly Fiberoptic	12-48	—	•	—	PMMA	PVC	—	—	•	2.2- 4.8mm	•	•	•	•	\$400- \$4500
Siecor Corp.	2-192	•	•	2700	Aramid	PE	—	—	—	15mm	DB, D, O, P	DB, D, O, P	D, P	DB, D, O, P	CF
Sumitomo Electric Research Triangle	4-96	•	—	2700	Steel/ FRP	PE/ PVC	—	—	•	.5"- .9"	DB, D, O	DB, D, O	DB, D, O	DB, D, O	CF
Toshiba Corp.	2	—	•	2500	Kevlar/ Metal/Wire	PVC	—	•	—	8.4mm	—	—	D	D	\$2.80
U.I. Lapp KG	1	—	•	300	Kevlar	PVC	•	—	—	5mm	—	—	P	P	\$1325
	2	—	•	300	Kevlar	PVC	•	—	—	5mm	—	—	P	P	\$1840
	1	—	•	300	Kevlar	PVC/ AL/PE	•	—	—	8mm	—	—	D, DBD	DB	\$2650
	2	—	•	300	Kevlar	PVC/ AL/PE	•	—	—	8mm	—	—	D, DBD	DB	\$3210
	4	—	•	700	Plastic rein- forced glass	PVC	—	•	—	13mm	—	—	D, P	D, P	\$7010
	6	—	•	700	Plastic reinforced glass fiber	PVC	—	•	—	13mm	—	—	D, P	D, P	\$9880
Key: DB = direct burial; D = duct; O = overhead; P = plenum															
															CF=Consult Factory

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Fiber End Preparation

The "scribe-and-break" and "lap-and-polish" methods are two straightforward techniques for preparing optical fiber ends for coupling. Both yield excellent results while requiring only minimal personnel training. When low-loss connectors are to be used, the lap-and-polish method is suitable. The scribe-and-break method allows more rapid preparation in situations such as fiber splicing, where unfixtured ends are involved. These techniques are primarily applicable to step-index, glass-on-glass multimode fibers and graded-index multimode fibers.

Jacket removal

The first step in fiber end preparation by either technique is removal of the opaque plastic jacketing and clear plastic buffering. This step may be simplified by taping the fiber cable to a flat surface so that the fiber end extends over the surface edge. Jacketing and buffering are carefully cut away with a single-edged razor blade or X-Acto® knife, or with a 0.3mm (0.012") wire stripper. Care must be taken to minimize abrasion of the pristine glass fiber.

Once the plastic is removed, the fiber is wiped clean with a wiping tissue wetted with isopropyl alcohol

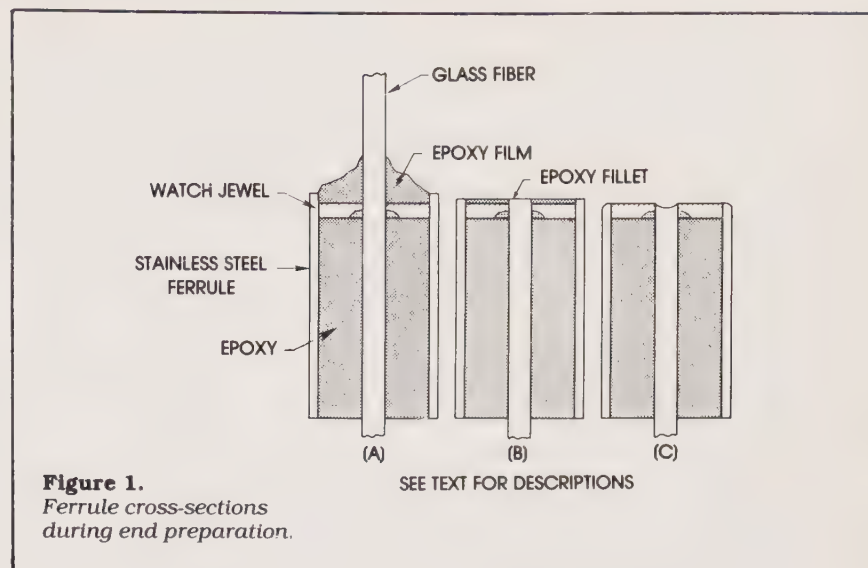


Figure 1.
Ferrule cross-sections
during end preparation.

or preferably Freon TF. The bare fiber is then ready for finishing.

The scribe-and-break method

In the scribe-and-break method, the stripped fiber is taped to a flat surface and pulled until it is under tension. A diamond-edged cutting tool is then used to nick or scribe the fiber. Once nicked, the fiber is put under more tension ($\geq 150\text{gmf}$ or $\geq 0.33\text{lbf}$) until it snaps. This force, even though applied by hand, produces smooth, flat fiber end faces.

Trained personnel can complete the entire scribe-and-break operation in one to two minutes. Mechanical scribe-and-break techniques also work well.

The lap-and-polish method

The second technique, lapping and polishing, is especially useful in connector installations where the fiber is fixed in a ferrule in the assembly of the connector. In this case, a bare fiber of the proper diameter is broken and inserted into a ferrule.

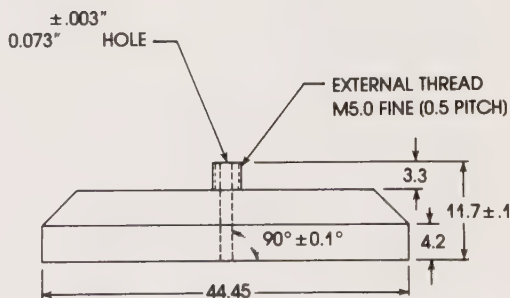
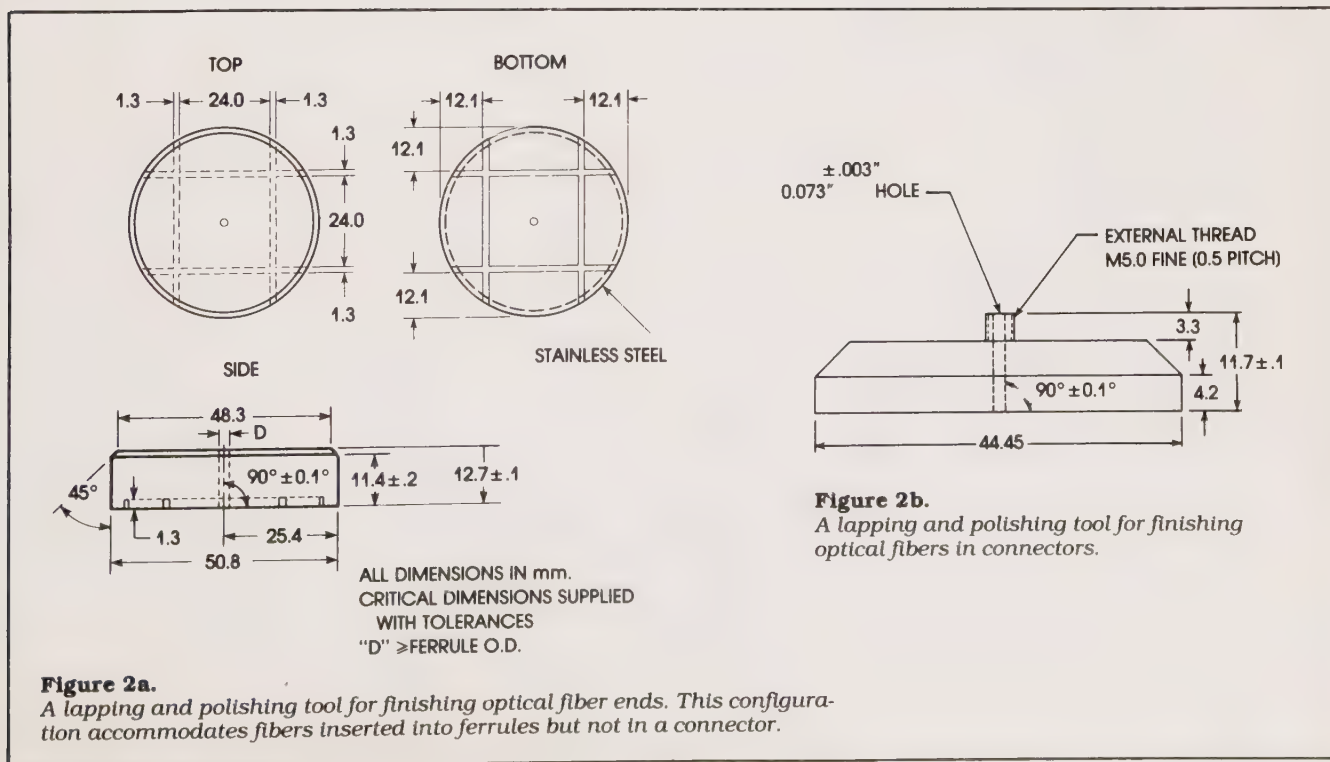


Figure 2b.
A lapping and polishing tool for finishing
optical fibers in connectors.

Epoxy is then applied to the ferrule. Any epoxy with the following characteristics should work well:

1. low viscosity, to allow wicking or suction into the ferrule;
2. good adhesion to glass;
3. reasonable pot life; and
4. short cure time at elevated temperatures, but not so short as to permit curing before the entire ferrule is filled.

If a connector is being installed on the fiber, the connector hardware must be on the fiber prior to ferrule installation. The epoxy is then applied, first to the back of the ferrule in which the fiber is inserted, and then to the front. For this operation, the ferrule should be heated to 80°C in the ferrule heating fixture. The epoxy should wick completely into the ferrule from the back, but if it does not, it can be drawn in the rest of the way by suction applied with a syringe through a small rubber tube, equal in diameter to the ferrule, attached temporarily to the ferrule front. With the epoxy in place, the entire assembly is heated

to 80°C for about one hour in the ferrule heating fixture to speed curing. The ferrule as it appears in Figure 1a is then ready for lapping and polishing.

A special lapping and polishing tool, designed like those shown in Figures 2a and 2b, is used to accomplish the end preparation. The tool in Figure 2a is used on ferrules without connector hardware, while the tool in Figure 2b allows the connector to be screwed in for support. Lapping is accomplished by moving the tool (with ferrule inserted) in a random motion on moistened, 600-grit, wet-or-dry adhesive-backed abrasive paper mounted on a firm surface. Throughout the lapping process, the ferrule end is inspected, and lapping is slowed when the ferrule shows evidence of having been ground flat. The front face of the jewel may be slightly recessed with respect to the ferrule at this point in the procedure. Lapping may be continued with light pressure to bring the jewel and ferrule planes just into or slightly short of

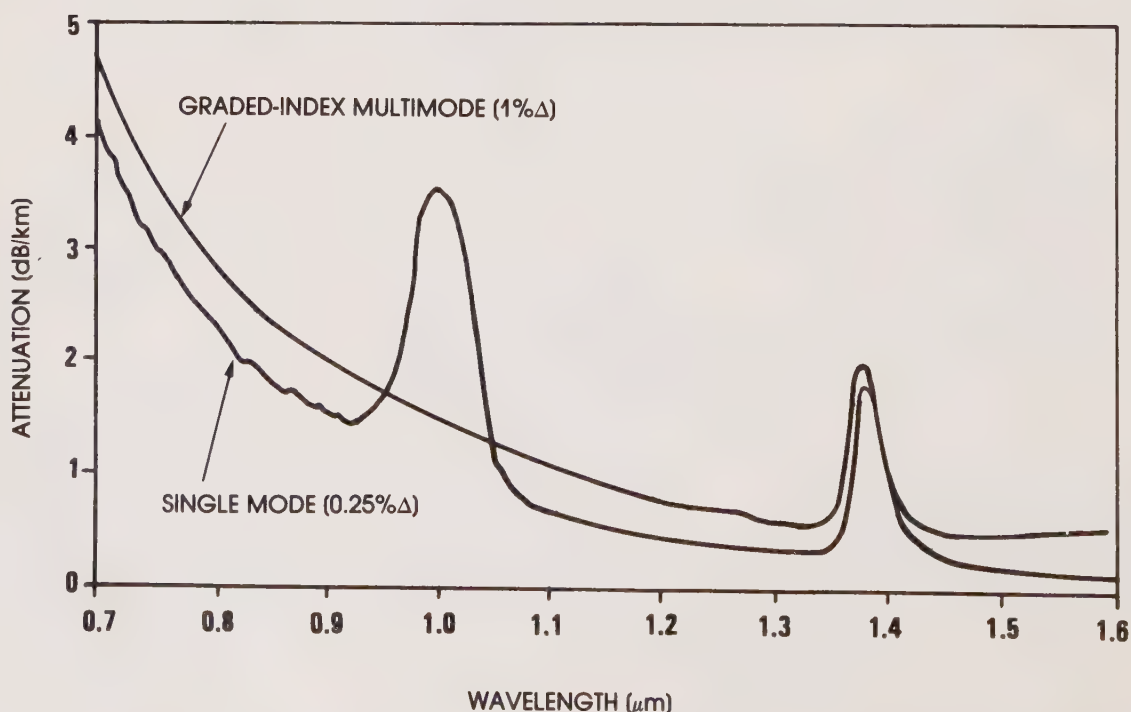
coincidence, as shown in Figure 1b, with a slight film of epoxy remaining over the ferrule end face. This procedure generally requires one to three minutes.

Polishing

Before the polishing step, the ferrule and tool are thoroughly washed to remove residual grit remaining from lapping. An Al_2O_3 polishing paste with suspended particles 0.3 to 1 μm in diameter is used as the polishing compound. This paste is applied to moist, adhesive-backed Pellon PAN-W paper mounted on a firm surface. Depending on the smoothness of the lapped surface, a well-polished surface can be obtained with moderate pressure in as little as one minute. The fiber surface will become very slightly concave and recessed with respect to the face of the jewel, as shown in Figure 1c. This characteristic is highly desirable for protection of the fiber during repeated connector matings.

Steven Storozum
American Photonics

High-Performance OVD Fibers: Attenuation Curve



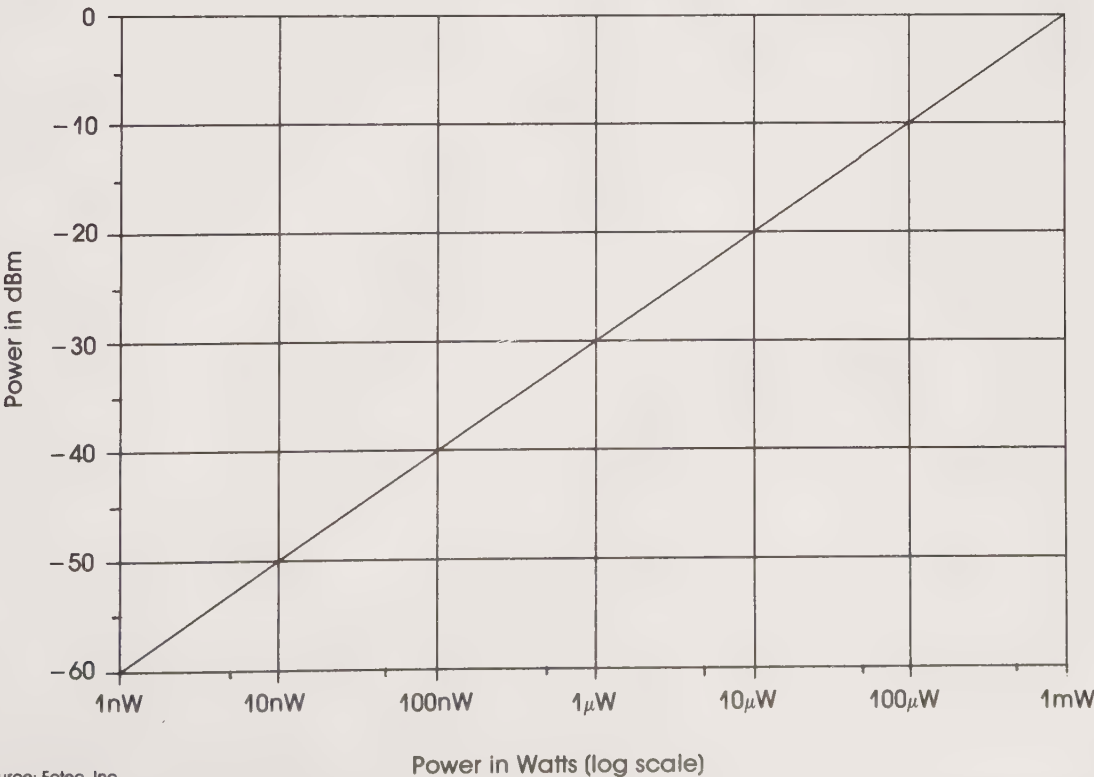
Source Corning Glass Works

dB to % Transmission Conversion
(dB = 10 log output over input)

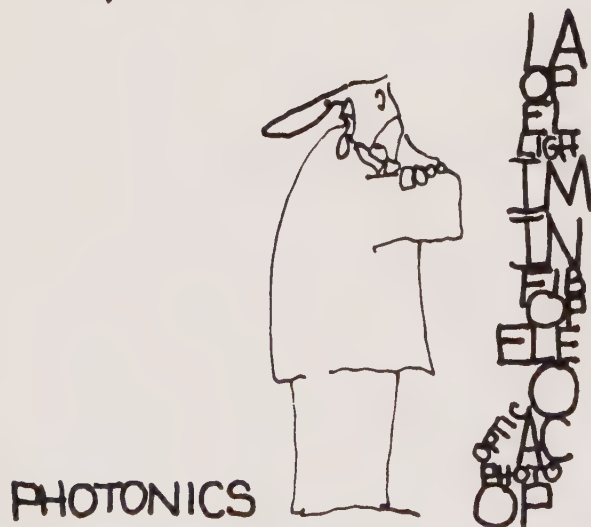
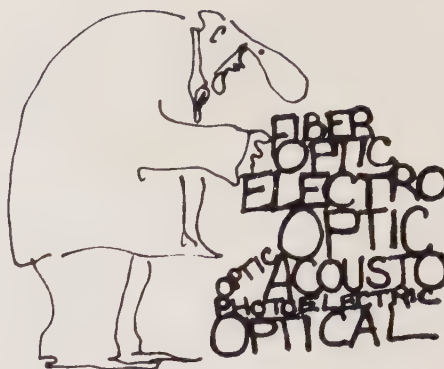
dB	%	dB	%	%	dB	%	dB
0.00	100.0	1.6	69.2	100.0	0.000	45.0	3.468
0.01	99.8	1.7	67.6	99.5	0.022	40.0	3.979
0.02	99.5	1.8	66.1	99.0	0.044	35.0	4.559
0.05	98.9	1.9	64.6	98.5	0.066	30.0	5.229
0.10	97.7	2.0	63.1	98.0	0.088	25.0	6.021
0.15	96.6	3.0	50.1	97.0	0.132	20.0	6.990
0.20	95.5	4.0	39.8	96.0	0.177	15.0	8.239
0.25	94.4	5.0	31.6	95.0	0.223	10.0	10.000
0.3	93.3	6.0	25.1	94.0	0.269	5.0	13.010
0.4	91.2	7.0	20.0	93.0	0.315	4.0	13.979
0.5	89.1	8.0	15.8	92.0	0.362	3.0	15.229
0.6	87.1	9.0	12.6	91.0	0.410	2.0	16.990
0.7	85.1	10.0	10.0	90.0	0.458	1.0	20.000
0.8	83.2	15.0	3.2	85.0	0.706	0.5	23.010
0.9	81.3	20.0	1.0	80.0	0.969	0.2	26.990
1.0	79.4	25.0	0.3	75.0	1.249	0.1	30.000
1.1	77.6	30.0	0.1	70.0	1.549	0.05	33.010
1.2	75.9	35.0	0.03	65.0	1.871	0.01	40.000
1.3	74.1	40.0	0.01	60.0	2.218	0.005	43.010
1.4	72.4	45.0	0.003	55.0	2.596	0.001	50.000
1.5	70.8	50.0	0.001	50.0	3.010	0.0001	60.000

Source: GTE

Fiber Optic Power Conversion Chart
dB to Watts



Source: Fotec, Inc.



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The table below lists charge-coupled imagers (CCDs) that have been used or are candidates for scientific applications. The pixel size is important in that, unlike the typical camera tube, with electron-beam readout, the CCD pixel dimensions are fixed, and this in turn dictates

the optical system focal length for a given resolving power. The "full well" or saturation level of the CCD is proportional to the pixel area and sets the upper limit to the dynamic range. The lower limit is determined by the CCD readout noise, which is expressed as rms elec-

trons per pixel. The readout noise in this table presumes optimum readout rates, usually below 1mHz, and correlated double sampling of the raw video signal to cancel out the CCD on-chip amplifiers' circuit reset noise. *John Lowrance
Princeton U. Plasma Physics Lab.*

Manufacturer	Format VxH	Pixel Size (Microns)	Full Well (Electrons)	Output Noise (Electrons) (rms)	Technology
TI	800x800	15x15	4×10^4	<10	POLY 3 ϕ
TI	800x800	15x15	10^5	50	POLY 1 ϕ
TI	1024x1024	18.2x18.2	2×10^5	50	POLY 1 ϕ
TI	584x390	22.4x22.4	3×10^5	50	POLY 1 ϕ
Fairchild	244x190	18x30	10^5	30	AI & POLY 2 ϕ
Fairchild	488x380	18x30	10^5	20	AI & POLY 2 ϕ
Fairchild	128x1024	20x20	10^6	300	POLY 4 ϕ
GE	244x380	30x30	10^6		POLY CID
Thomson-CSF	576x384	23x23	4×10^5	50	POLY 4 ϕ
RCA	512x320	30x30	6×10^5	50	POLY 3 ϕ
RCA	256x403	20x16	2×10^5	50	POLY 3 ϕ
RCA	1024x640	15x15	1.5×10^5	50	POLY 3 ϕ
GEC	576x385	22x22	2×10^5	<20	POLY 3 ϕ
GEC	1500x1500	23x23			
ITEK	96x2048	13x13	1.5×10^5	100	POLY 8 ϕ
ITEK	48x1024	24x26	4×10^5		POLY 2 ϕ
Tektronix	2048x2048	27x27	5×10^5	<20	POLY 3 ϕ
Tektronix	512x512	27x27	5×10^5	<20	POLY 3 ϕ
Amperex	588x604	15.6x10	1.7×10^5	100-200	POLY 4 ϕ

Manufacturer	Illuminated Surface	Peak QE (%)	Spectral Response Range (nm)	Readout Mode	Application
TI	Back	80	120-1000	Frame Transfer	Space
TI	Front	45	400-1000	Frame Transfer	Space
TI	Front	45	400-1000	Frame Transfer	Development
TI	Front	45	400-1000	Frame Transfer	Standard TV
Fairchild	Front	30	400-1000	Line Transfer	Industrial
Fairchild	Front	30	400-1000	Line Transfer	Standard TV
Fairchild	Front	50	500-1000	TDI	Periscope
GE	Front	30-40		X-Y Address	Industrial
Thomson-CSF	Front	50	400-1000	Frame Transfer	Standard TV
RCA	Back	80	350-1000	Frame Transfer	Science
RCA	Back	70	350-1000	Frame Transfer	Standard TV
RCA	Back	80	350-1000	Frame Transfer	Science
GEC	Front	30	400-1000	Frame Transfer	Science
GEC	Front			Frame Transfer	Development
ITEK	Front		400-1000	TDI	Airborne
ITEK	Front		400-1000	TDI	Airborne
Tektronix	Back	80	350-1000	Frame Transfer	Science
Tektronix	Back	80	350-1000	Frame Transfer	Science
Amperex	Front	20	400-1000	Frame Transfer	Standard TV

POLY = polysilicon
 ϕ = phase

CID = charge-injected device
TDI = time-delay integration

Source: 1984 Paper Summaries, International Electronic Imaging Conference, courtesy Institute of Graphic Communication

Digital Image Processing

Digital image processing is the technique by which an image taken from the "real world" is converted by any of several means into a finite array of points, each represented by some numerical value. This array can then be processed for a wide variety of purposes, including being displayed on a television monitor, printed onto film or reduced to some new set of data such as numerical tables, charts, graphs or images.

Uses of digital imaging technology include: image coding/decoding for transmission and storage; image analysis, either automatically by machine or interactively by a human operator; data-set comparisons and modeling for creating new data sets that represent the correlation of varied inputs; picture enhancement and restoration for interpretation; picture enhancement and manipulation for graphic arts purposes; and machine vision for robotics and automated test, measurement and inspection systems.

In some cases, digital image technology is required simply to create a viewable display of otherwise non-visual information. Thermal radiation sensors benefit from this use of the technology, as do radar, gravity and magnetics, radio and other sensor systems that operate within electromagnetic spectral ranges invisible to the human eye. Also, nonvisual information generated directly by signal-processing techniques — usually a computer (digital) task — can be organized into viewable displays. This class of information includes seismic data, computed axial tomography (medical "CAT scans"), ultrasound scanners and one of the newest of medical diagnostic technologies, that of nuclear magnetic resonance (NMR).

Some imaging devices directly create digital images by converting, at the sensor stage, a real-world image into a finite array of numerical elements representing variations of emitted or reflected spectral energy. These sensors include charged-coupled devices (CCDs) in either one or two-dimensional arrays, drum-type scanners, "pushbroom" scanners and orbital and aerial multi-spectral scanner systems (MSS).

Digital imaging and memory

Not all applications incorporating the use of imagery require the sophistication — or can justify the cost

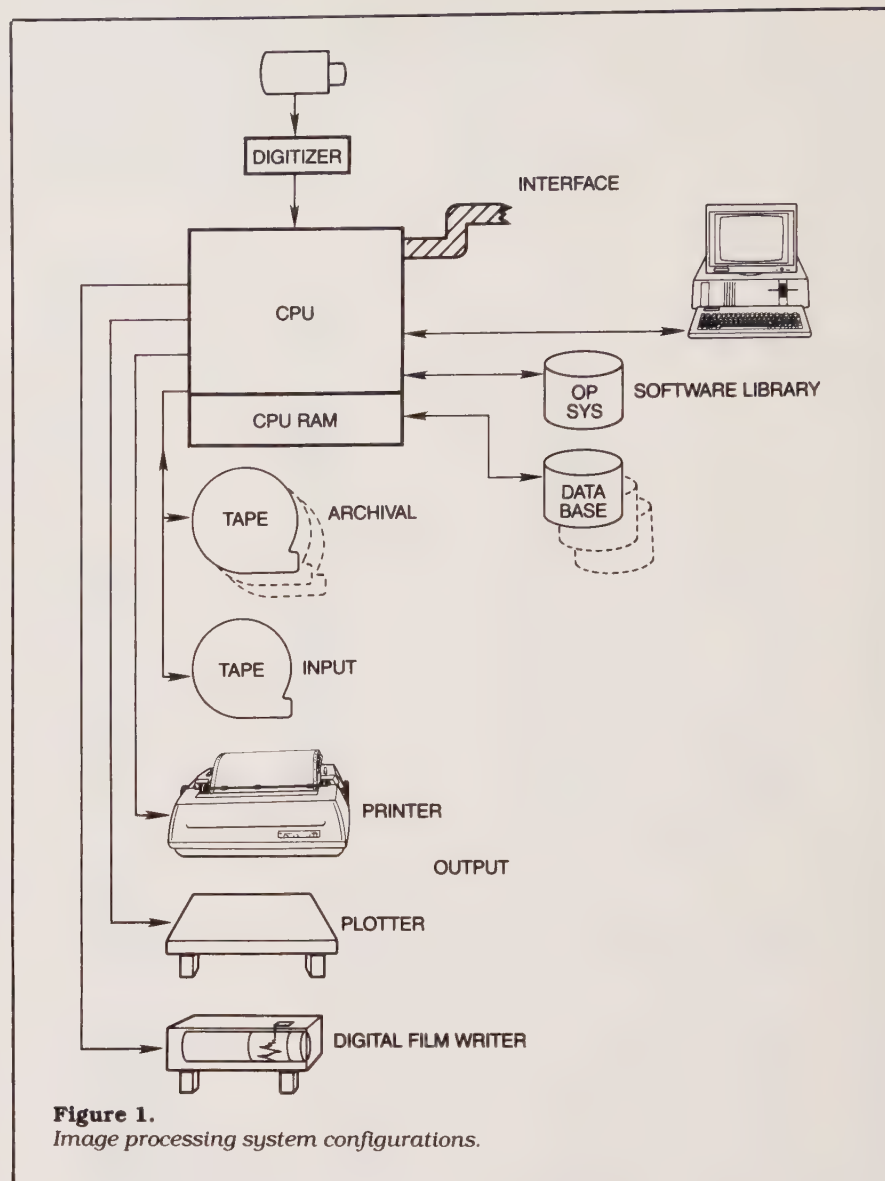


Figure 1.
Image processing system configurations.

— of digital image processing or display. As electronic technology continues to increase in performance/cost ratios, however, more and more uses for digital image processing are emerging. Advances in VLSI technology have created vastly more powerful processors in smaller, less costly configurations, and coupled with the relative decline in cost-per-bit of semiconductor RAM, have led to a continuing decline in systems cost. Just five years ago, for example, many imaging systems used 4K and 16K static and dynamic RAMs for bulk memory, but typical systems today use 64K RAM. Predictions are that 256K RAM will be available in quantity in the very near future, allowing for production de-

signs based on those circuits. The next evolution will be 512K and 1024K RAMs, further improving the performance/cost ratio.

The issue of memory cost is particularly significant to digital image systems because of the special nature of the data involved: a single, full-color (RGB) image with a resolution of 1024×1024 pixels (picture elements) and a data precision of 8 bits per color component requires three million bytes of memory for storage. This represents the state of the art in digital television display.

For a digital image exceeding television display refresh bandwidths (roughly 8 to 118 MHz), consider the example of a LANDSAT satellite Thematic Mapper (TM) scene, com-

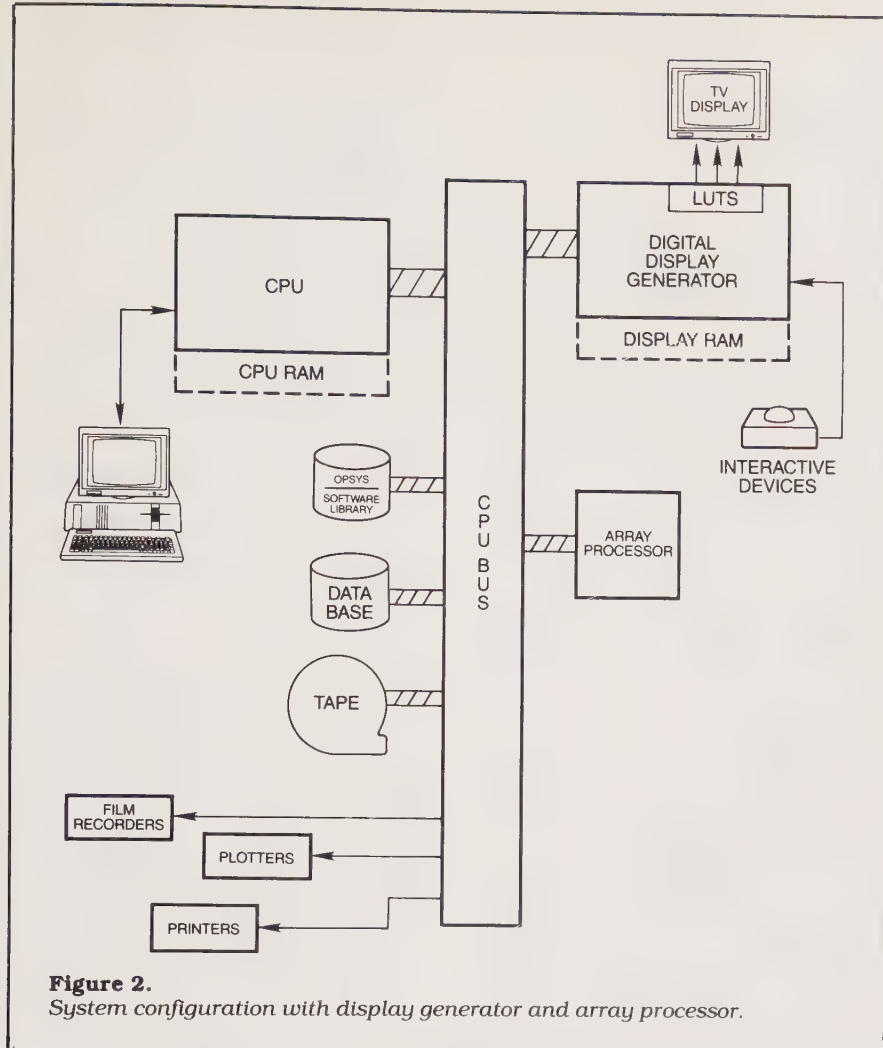


Figure 2.
System configuration with display generator and array processor.

posed of about 6000 lines of 6000 pixels each: One scene is scanned and recorded in seven separate spectral bands (UV, blue, green, red, IR, thermal). Since each pixel is stored as an 8-bit byte of information, the total memory requirement for storing one scene is about 250 Mbytes.

The evolution of digital image processing since the early 1970s has been along two distinct lines: "batch" processing of image data and interactive processing and manipulation of digital image displays. Because of technological advances, these two techniques have followed convergent paths of development: Digital displays now have greater resolution, and the active RAM memory of display systems has steadily grown larger. Whereas only a few years ago most display systems were limited, by memory cost as well as technology, to 1 Mbyte or less of image-storage RAM, some systems today provide off-the-shelf capacities of 8 Mbytes.

Future use of 256K RAM chips will quadruple this capacity. In addition, the development of very-high-speed read/write capabilities for digital

disk storage will make it possible to "roam" or movie-loop through data bases in excess of 1 gigabyte in real time ("real time," for the purpose of this article, is one frame every 1/30th of a second).

Processing architectures

Digital image processing systems, like all digital systems, are composed of two fundamental elements, hardware and software. In some systems, the software is highly device-dependent; in others, the software is modular, transportable and generalized. Both have their advantages. Hardware configurations partially define the type of software to be used in a system, as illustrated by the following examples:

In the traditional image processing system configuration (Fig. 1), digital image data is input by digitizing analog video or by acquiring the data in digital form already from magnetic media or an interface to another system. The system illustrated, which has no dynamic display, typically is used for batch processing. The software can be general and modular, since it may be used

on any type of CPU. Such a system can be used to create imagery by applying to it certain known functions (contrast enhancement, sharpening, color modification, etc.). The result of the processing may simply be alphanumeric reports (feature classification, counts, mensuration, etc.), or output to either a printer or a terminal. Other outputs may be to plotters or digital film recorders so the operator can view the result of processing as a real image.

While such a system may be the most flexible in its ability to accommodate many different types of software routines, it will also be relatively slow in processing, depending on the power of the CPU used. This type of system may also represent the lowest cost in relation to the magnitude of data.

The greatest disadvantage of this system is that it is not interactive. Miscalculations, errors and failures may not become evident until literally hours of CPU time have been devoted to a single process. Since no computer is optimized for managing huge contiguous blocks of data — common to all digital images — the CPU generally must be dedicated to image processing tasks, be very powerful or be aided by high-speed parallel processing peripherals, which adds considerably to cost.

The configuration in Figure 2 essentially adds two hardware devices to the first system: the digital display generator, which creates television displays of images stored as data in local RAM memory; and the array processor (AP), used here to address the specific task of executing the complex functions on data arrays associated with digital imagery at rapid rates. The use of the array processor enhances a CPU's throughput capabilities by factors of 10 to 100, allowing for the use of a smaller, less costly CPU, and a realistic capability for multiple users.

The digital generator also tremendously enhances the potential capabilities of the system by allowing the operator to exercise certain processing functions rapidly, view the results, make immediate modifications, store the resulting process parameters, and use those parameters as a basis for batch processing of disk or tape-based data, all aided by the array processor.

Such a configuration may still be able to accommodate general image processing software packages, but with the introduction of the digital display generator some software will become device-dependent — particularly those portions of a functional library affording the user interactive

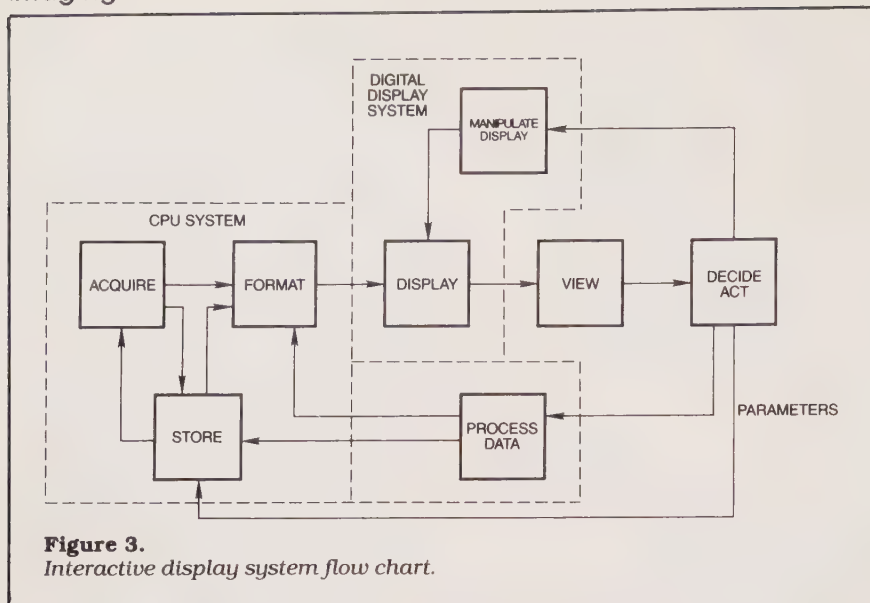


Figure 3.
Interactive display system flow chart.

control and manipulation of the displayed image.

This system offers advantages over that illustrated in Figure 1: interactivity, a tremendous improvement in processing throughput, and the capability for many users on one system. The system also adds certain functional capabilities inherently absent on the previous system, including the capability of using it in dynamic human interpretation and analysis of imagery.

Tracking the system at work

Figure 3 is a flow chart of an interactive digital display system performing an analytical task. Having acquired the digital data, the system formats the data for television refresh and display or stores it for later use. The formatted data is then transferred from the CPU local environment to the local environment of the digital display generator, where the operator can view the image on a television display for subsequent analysis or interpretation.

The operator may choose to manipulate the display by altering contrast or color, "roaming" or panning the image, digitally "zooming" the picture, or various other functions. If the operator elects to perform some transform on the data itself (represented by the "DECIDE/ACT" box), the appropriate instructions are given to the CPU, which processes the data accordingly. The data input for this processing may be the originally acquired data, the data in storage or the data held in display memory (represented by the "DISPLAY" box). The result of this processing can be redisplayed, allowing the operator to continue the procedure of modification, viewing, decision and action. Besides being able to store

the result of a process, the operator can also store the parameters by which the process occurred for later use on other images or on a larger image data base processed in the batch mode.

This configuration also has certain disadvantages, especially cost. The addition of a display generator and array processor may increase system cost by \$100,000 to \$150,000, exclusive of the software to operate these peripherals. This configuration also has the disadvantage of being device-inefficient: Typically, the array processor is capable of far more powerful processing than it will be required to do, and during the interpretation and analysis period, most of the system will be idle. Since most of the digital display generators manufactured during the 1970s have little or no local intelligence, such a system must be controlled by the host CPU, both in functionality and in user/device communications.

Another major disadvantage of this configuration is the complex path both data and commands must take during routine processing. An operator instructs the CPU to instruct the display generator to perform a function, which requires the CPU to fetch data from storage or form the display generator's RAM memory, bring the data in manageable blocks over the CPU bus to the array processor, execute some transform, send the result in manageable blocks back to the CPU bus and into the RAM memory of the display generator for display. The I/O overhead associated with such configurations may run as high as 99% of the processing time need for a given task. Therefore, a function which may require only microseconds to perform on the array processor may take sev-

eral seconds to complete before the result can be viewed on the display.

In later evolutions of the digital display generator, some of the processing capabilities formerly confined to the CPU/AP partnership were established in hardware or in hybrid, semi-intelligent components within the display generator. In some cases, hardware execution of processing tasks (with no operator-directed software modifications of parameters or coefficients) is appropriate. These can be straightforward arithmetic functions such as image additions and subtractions, simple low-pass filters (for smoothing), high-pass filters (for sharpening), and lookup table operations such as contrast stretching and pseudocoloring of monochrome images. In other types of processes, noninteractive hardware functions are generally inappropriate.

Special-purpose architectures

A third class of digital image processing system configuration, developed in the early 1980s, incorporates the components of the previous configurations into a contiguous bus structure, along with special-purpose processors optimized for processing large digital arrays. Since computers are general-purpose devices incapable of simultaneous processing of these large arrays, this new architecture incorporates special-purpose devices such as algorithm-driven processors that relieve the CPU of almost all data processing functions. In this architecture, the CPU acts primarily as a system controller, command parser and file manager.

To accomplish this, the system includes a CPU bus (in the example shown in Figure 4, the CPU is the Motorola MC68000 16-bit microprocessor, and the control bus is the Motorola VERSABUS), with multiple high-speed bus pipeline for memory-processor-memory transfers, eliminating the bus-to-bus I/O overhead inherent in the architectures shown in Figures 1 and 2.

The multiple-bus architecture in the high-speed image processing pipeline is capable of simultaneously addressing various processing devices and various blocks of memory, which can in turn be logically reconfigured by software command to any image size (e.g., 512×512 , 1024×1024 , 256×512 , etc.). Since the bus architecture is designed to update stored values in image memory every video frame time (1/30th of a second), any processing function that can be accomplished by a processor in one video frame or faster

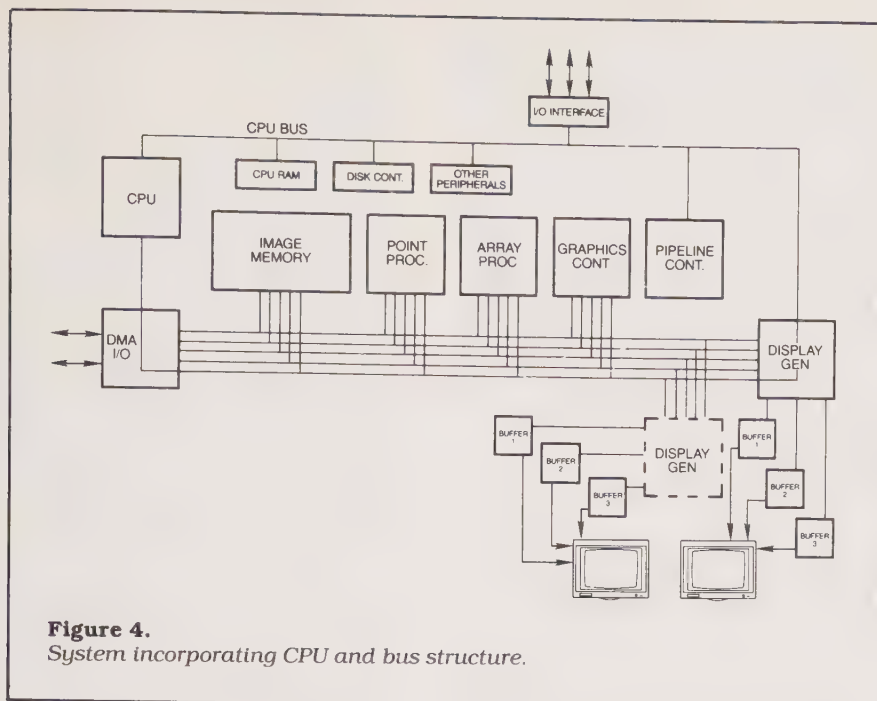


Figure 4.
System incorporating CPU and bus structure.

can be executed and displayed in real time. And since the CPU is now free of the computationally intensive requirements of the previous architectures, realistic multitasking is possible. Because the special-purpose processing modules (array processor, point processor, display controller, etc.) are locally intelligent, they can maintain themselves during their special tasks while the CPU is sending instructions to the system to execute other independent tasks.

This multitasking is accomplished through the use of a pipeline controller that accepts instructions from the CPU as microcode, parsed from high-level commands entered by the operator at a keyboard or function key panel. Having downloaded a particular task to the pipeline controller, the CPU is then free to address other tasks. The pipeline controller is responsible for loading the appropriate coefficients, parameters and tables into the special-purpose processors, using state code for the task required. It also has the responsibility of assigning the appropriate bus (read, write or control) to the appropriate device register and starting addresses in memory.

And because the display controllers shown each have sufficient local intelligence and bus-independent display buffers, multiple independent displays can be supported and manipulated by different operators. In the example shown, the operating system is the Motorola VERSADOS, which is a 32-tasking system. Therefore, in addition to having two display functions carried on simultaneously, other operations, such as pro-

gram development in FORTRAN or Pascal, and file maintenance using standard system utilities could be going on concurrently. Such a system allows for interface to another computer or network for data exchange and other purposes.

The cost advantages of such a system are evident in the architecture. Since the CPU exists as a board set, and all other special purpose processors also are designed as single boards or board sets that plug into the same backplane, the base mechanical costs of multiple chassis, card cages, power supplies, fan housing and the like are eliminated. Also eliminated are the requirements for special hardware and software interfaces for the array processor, display generator, etc. At the same time, requirements for batch processing still could be executed on the CPU or, for larger tasks, on a separate host computer.

Statements about future architectural developments in digital image processing systems are, like any form of prediction, largely conjectural. However, certain basic trends are emerging from the current stage of digital technology.

1. Since CPUs are largely general-purpose machines, they will probably continue to be used as system controllers. Multiple CPU chips may be incorporated as parallel processing devices.

2. Because of the peculiar nature of digital image data in large arrays of potentially very high precision (8, 10, 16, 24, 48 and 64 bits per pixel), special-purpose data processing devices are here to stay. They doubt-

less will continue to be developed for more speed and more computational precision.

3. Semiconductor memory costs are decreasing steadily, and this should lead to larger and larger internal bulk-memory capabilities in systems. New memory technologies are constantly being investigated.

4. A distributed task architecture, integrating compact special-purpose devices, can be efficient and cost-effective. Further developments under such an architecture will allow the upgrade of existing systems to new capabilities by replacing or adding new boards.

Image processing examples

While current applications of digital image processing are extremely varied, the functions by which these diverse applications utilize the technology fall into a finite category of equations and algorithms.

For instance, take two seemingly different tasks such as the need to determine if an object on the ground has been moved, even slightly, between May 1 and May 5, and the task of determining whether a complex piece of manufactured product (such as a fully populated PC board) is missing any pieces.

In the first case, common to aerial surveillance applications, two photographs or image scans of the same area are taken on the two dates listed. Let the May 1 image be represented by $A_{(j,k)}$ and the May 5 image be $B_{(j,k)}$, where j and k are the column and rows which define the grid coordinate location of the pixels in the image. The values for A and B are defined by some number falling within the precision of the system in use. In this example, let us assume a 12-bit potential precision, with a true dynamic range (within the limits of the scanning device itself) of 8 bits, or 256 shades of grey.

A simple subtraction of B from A will show whether an object has been moved. But first the two images must be geometrically rectified for registration. Such rectifications are accomplished by any of a variety of algorithms using interpolation, nearest-neighbor averaging, or "warping" through the use of complex polynomial operators. Assuming that the registration is correct, the result of the subtraction will be

$$A_{(j,k)} - B_{(j,k)} = C_{(j,k)}$$

If the object has moved, it is assumed that the brightness value at the point where it once sat will be changed, such as would happen if a bright object on a dark background was

taken away or moved to another location against the dark background. In this case, $B_{(j,k)}$ will have a lower value than $A_{(j,k)}$. The result of the subtraction will be a relatively high amplitude value for the pixel defined as $C_{(j,k)}$.

For every point where there has been no change, the resulting value will be 0 (in a system where the conditions and scanner are perfect). Therefore, all non-zero points in the image can be identified by transforming them into a binary map. Where the object in A was dark against a light background, the result of the operation also will be a non-zero value, but negative in amplitude. The same mapping procedure will be used. Such a task is accomplished in the last architecture shown in one frame. In the other task, where a PC board is being inspected, $A_{(j,k)}$ represents an image permanently stored in memory for control purposes, while $B_{(j,k)}$ represents an unknown board on an assembly line. The results and the function are the same.

All simple arithmetic operations are performed on such systems on a point-to-point basis. These include the summing of two or more images to reduce sensor noise by averaging; the creation of a luminance component of multispectral imagery by summing and averaging; the logical combination of two images (OR, AND, etc.); the addition, subtraction, division or multiplication of an im-

age by a constant value, and so forth.

Also performed on a point-to-point basis are table operations, where an input value is mapped to some different output value. Contrast enhancements, inversions, stretching and pseudocoloring are accomplished using these methods.

More complex image processing functions incorporate both arithmetic functions and spatial functions. One pixel output value is changed according to the values of neighboring pixels, either adjacent or at some defined distance. The geometric rectification mentioned earlier is a complex example of such a function.

A simple example might be to shift an image one column or row up, down, left, or right. In this case, the value of the pixel at point m,n will be replaced by the value of the pixel at point, $m-1,n$ where the image has been shifted one row down. The next level of complexity is the case where the image is passed through a spatial filter. Here, a matrix of coefficients is placed over the first two-dimensional array of the image (typically, the upper left corner), and the corresponding pixels beneath the matrix are multiplied by the associated coefficients in the matrix (in a 3×3 matrix, divide by 9). The new number replaces the value of the image pixel in the center of the 3×3 array.

Having accomplished this first kernel calculation, the filter matrix then is moved one column to the right. Calculations on the input pixel

values are executed and replace the center value. The matrix is then moved throughout the image. A 512×512 image requires 2.36 million multiplications and 2.36 million sums, with 262,144 divisions between. Larger filter matrices are used as applications require.

The use of matrix filters is varied, but can be generated to perform an impressive list of specific functions, including image "smoothing" (a low-power filter where the coefficients of the matrix are all 1), image sharpening, edge detection, feature erosion and dilation, etc.

Because almost all operations and functions listed here can be made automatic in a computer-controlled system, and because almost all operations can be executed in real time using the third of the illustrated system architectures, applications in artificial intelligence, robotics, automated inspection and analysis now are possible.

Because the system displays results rapidly, the uses of digital imagery for human visual interpretation and analysis are vastly enhanced over former architectures.

And because costs associated with high-technology digital systems are constantly on the decline, the use of digital imagery for many applications formerly requiring analog, electronic or photographic processes is growing rapidly.

*Richard Pendergrass
Vicom Systems Inc.*

Imaging in a Computer Environment

The rapid growth of powerful microcomputer systems has greatly benefited scientific and engineering applications that previously required large minicomputers or mainframes. Undoubtedly, the cost-performance ratio of 16- and 32-bit computers is outstanding for processing speed and user environment, but these computers are not particularly well designed — from the system architecture standpoint — for image acquisition and analysis. Entry of microcomputer technology into image-acquisition tasks has forced the user to determine the demands of digital imaging and how specialized subsystems allow these applications to be integrated into the general-purpose computer environment.

To begin with, we define "high-performance digital imaging" as those applications that are not easily supported by standard vidicon image-sensing tubes used with low-cost digitizer boards (frame grabbers) that plug into various microcomputers. The imaging systems related to more advanced applications are fundamentally similar in that the spatial distribution of brightness values recorded by some kind of electronic sensor is ultimately converted into a number that may be processed by a computer. However, as the need for flexibility and accuracy increases, the approach based on the vidicon becomes more and more inadequate.

Pixel-level image quality

The number of individual picture elements (pixels) into which a brightness distribution is divided is often called an index of spatial resolution, and the number of brightness values discernible from a given pixel is the contrast resolution. A moment's reflection will reveal that in some ways these two terms are highly interactive: A scene with high spatial resolution, but limited contrast resolution, might have much less useful information than the same scene organized with low spatial resolution but very high gray-scale resolution. Furthermore, the geometric stability of the image-forming aspect of the sensor and the sensor's read-out technique also interact with spatial and contrast resolution to influence image quality. This system of phenomena determines the accuracy,

or quantitative reliability, of each pixel.

One of the first steps to gain control of this situation is to establish absolute sensor geometry accuracy. Solid-state image sensors (photodiodes, charge-coupled arrays or CCDs) are produced using integrated circuit fabrication techniques and have inherently much more uniform pixel area and more accurate pixel placement than vacuum-tube vidicons. Furthermore, each pixel in a solid-state sensor is a discrete physical entity. In the case of vidicons, pixels are produced by the time division of a scanning beam, so that any jitter in the process adversely affects the geometric and brightness accuracy. Figure 1 illustrates a typical solid-state sensor response.

A given pixel in, for example, a CCD device has its individual imperfections; however, the particular characteristics of a given CCD pixel may be characterized quite accurately, and the corrections required are stable over relatively long periods of time. Those familiar with the technology will recall that solid-state sensor pixels may have slight gain or responsivity variations, as well as an offset value, but that the devices are highly linear, allowing exact calibration. Depending upon the particular device fabrication technique, an individual pixel may have a dynamic range of 1000 to 10,000 or more.

This wide dynamic range supports extremely high contrast resolution, and if the dynamic range is divided up linearly, 8, 12 or 14-bit accurate brightness values may routinely be obtained. This high contrast resolution, together with broad dynamic range and absolute geometric stability, make the solid-state pixel highly suited for demanding measurement applications.

Pixels in solid-state detectors are also quite free from "memory," in that reading out an element resets the pixel. In most cases, once a pixel is read it immediately resumes accumulating an electrical charge related to the light falling upon it. In some more specialized devices, a pixel, once read out, may be held in an insensitive mode until a new measurement is needed, reducing the "dark current" artifact whereby, given a long enough interval of time (generally a few seconds) a sensor element would spuriously "fill up" because of passive electrical leakage.

So, for applications requiring high accuracy and numerically-oriented results, solid-state detectors are a necessity. In fact, their inherent quality and stability make subsequent portions of the overall image analysis process much easier and more reliable.

One of the basic parameters of digital image acquisition is how long it takes to read out a frame. To estimate the frame time, simply multip-

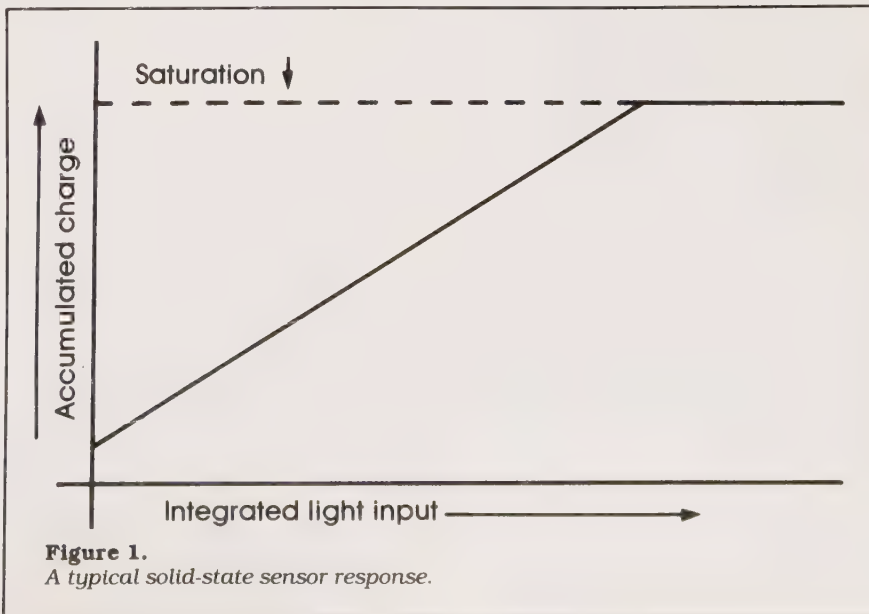


Figure 1.
A typical solid-state sensor response.

ly the number of pixels in the solid-state detector by the amount of time it takes to read (which also means reset) each element.

For example, a 576-by-384 element CCD sensor, read out at a rate of 200 nanoseconds per pixel (i.e., a 5.0MHz pixel rate), would take about 44 milliseconds per frame, or around 20 frames per second. A smaller 128-by-128 detector read out at 125 nanoseconds per pixel, or 8.0MHz, takes only around 2 milliseconds per frame. The latter provides adequate resolution for many applications, given its 8-bit per pixel contrast resolution capability, at a rate of several hundred frames per second.

In addition, the 128 squared and companion 256 squared devices allow the user to select partial frames by limiting the number of lines forming the image. So, to achieve a frame rate of 1000, the small detector can be operated as a 32-by-128 element device (see Figure 2). Both these devices can be externally gated, or activated, so that only visual phenomena during a precise interval are recorded providing high temporal resolution.

The variable frame-size feature can be invoked during the middle of data acquisition, so that any real-time processing going on in parallel may be performed upon a selected subregion of the full frame. For example, once a feature has been extracted from an initial frame, and its position determined, only relatively small subsequent frames, bracketed around the feature, would be required. These subframes can move up and down within the full frame as the feature of interest moves.

At the present time, the largest commercially available solid-state sensors have about 600 by 400 pixels; larger format sensors under development should provide 1024-by-1024 element units capable of operation in the visible region within the next few years. Although the largest solid-state two-dimensional array is somewhat smaller than the highest resolution vidicons, the inherent higher quality of the pixel data from the CCD detectors often results in more usable information despite the lower number of pixel elements.

The above discussion is based upon two-dimensional, matrix sen-

sor arrays in which integrated circuit fabrication techniques limit the maximum number of pixels, giving these devices the advantage of relatively quick readout. On the other hand, for applications in which image-acquisition time is not important, linear arrays with up to 4096 elements can be used to form large-format images with relative motion of the detector and subject used to produce a two-dimensional array of brightness values in the computer. Applications of this approach range from capture of flat artwork and gel electrophoresis analysis to flow visualization of fluorescing material.

Thus, the flexibility of solid-state sensors allows variable frame size and rates to be selected according to both the static and dynamic requirements of the application. Given that images generally consume large amounts of computer resources, both with respect to memory and subsequent processing, being able to allocate image frames to "fit" the phenomena both reduces work and conserves resources throughout the system.

As image-acquisition and measurement devices rapidly change from desktop to computer-controlled subsystems, it is important that the special demands of imaging coexist with microcomputer hardware and software capability. For example, the 8.0MHz pixel acquisition rates mentioned in the previous section exceed the input rate capacity of even high-performance microcomputers by an order of magnitude. Furthermore, in a real-world situation, where the host microcomputer is processing numerous other tasks such as data reduction, communication and control simultaneously with image data acquisition, the maximum pixel input rate using conventional approaches would be very low.

Clearly, it is not possible for the incoming pixel stream to be injected directly into the workload of a microcomputer or minicomputer without causing severe disruption of other ongoing processes. The answer to this problem is to uncouple the two processes by the use of large, dual-ported buffer memories to which both the host computer and the image-acquisition hardware have access (see Figure 3). Compared to the pixel input rate, the host computer needs access to the memory relatively infrequently, making a multiported memory possible, and allowing other higher-speed devices (optical disks, for example) to be loaded from the buffer.

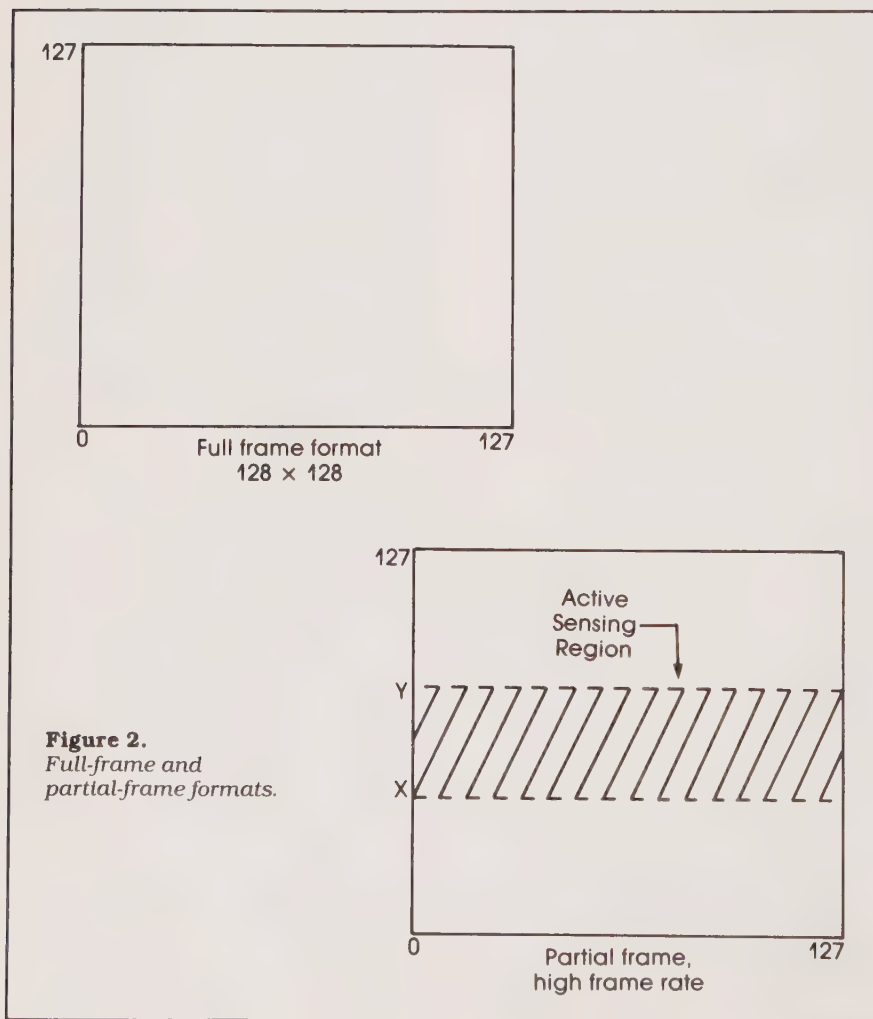


Figure 2.
Full-frame and
partial-frame formats.

Figure 3.
Host address space inside microcomputer showing footprint of dual-ported image memory.

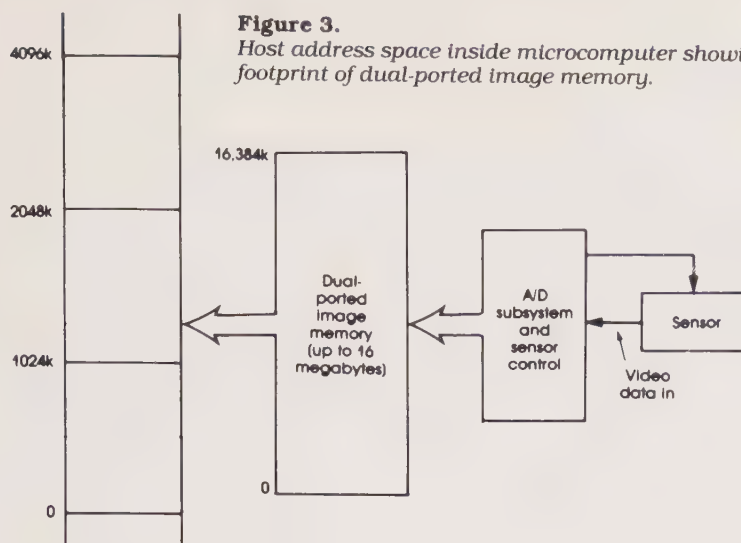
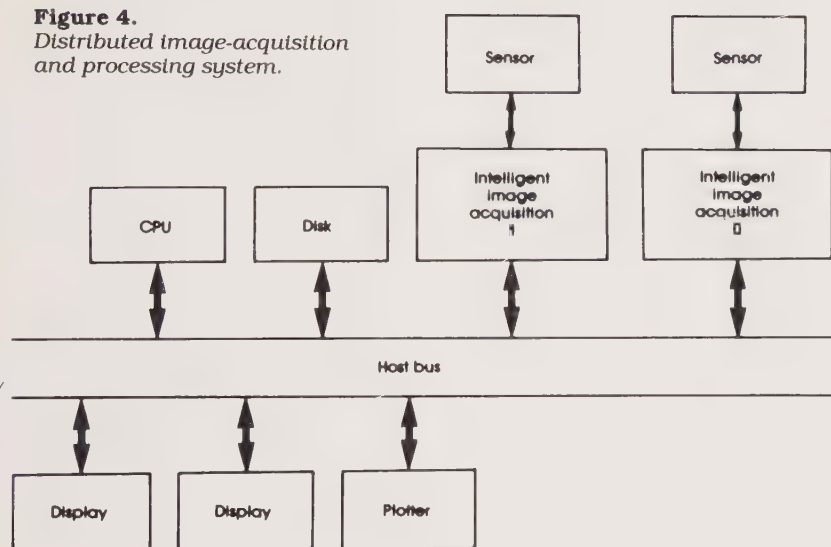


Figure 4.
Distributed image-acquisition and processing system.



Low-cost high-speed dynamic memory allows entire images to be kept "memory resident" at reasonable cost. Modern microcomputer operating systems such as Digital Equipment Corp.'s VMS, which runs on their MicroVax computer, have high-level programming language support permitting very large numerical arrays to be processed easily. And having the entire image in memory means that numerical operations will proceed radically faster by virtue of the computer operating system's ability to deal with them as monolithic entities, and because all pixels in the image are immediately available to the host hardware.

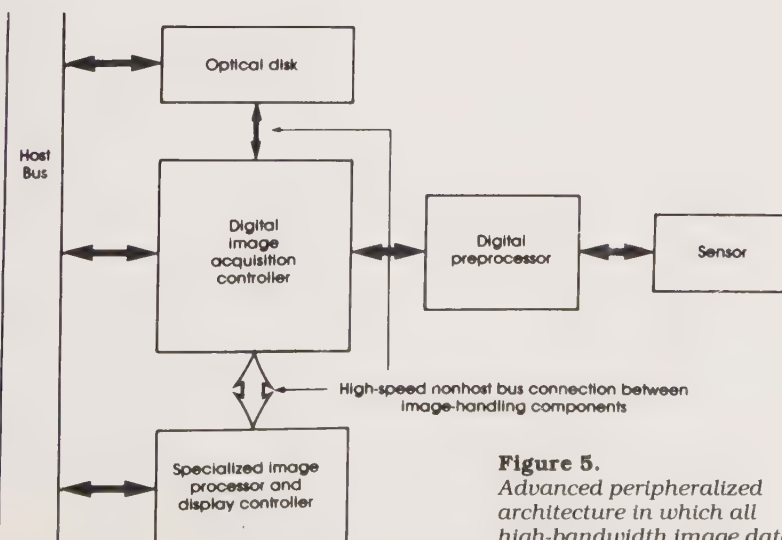
For more complicated applications, in which it is necessary to capture images from several different sources at the same time, the intelligent image-acquisition subsystem approach described above would allow multiple channels of image data to be taken from a single microcomputer. Variations on this theme, such as having simple preprocessing of the image occur in the subsystem on the incoming pixel data stream, further reduce data volume and subsequent workload (see Figures 3 and 4).

These high-performance, solid-state digital imaging systems are finding increasing use in such demanding applications as coherent anti-Stokes Raman spectroscopy, image archiving and distribution, human factors research and other areas requiring automated acquisition of naturally occurring (i.e., uncooperative) image-mediated events. Of course, solid-state detectors may be conveniently integrated with advanced solid-state image intensifiers to more easily capture phenomena that are high-speed, low-light and at randomly-spaced intervals.

Because image data tends to occur in large volumes, it's becoming more apparent that hybrid preprocessing circuits should be colocated with the image sensor itself so that less and less processing work need be done by the host microcomputer (see Figures 4 and 5). This approach — peripheralizing the visual analysis — is one often found in nature. Conversely, as the user's appreciation of functionality and "friendliness" becomes more dependent on large-scale software systems, flexible and modular hardware implementation of image acquisition and processing functions further isolates the user-interface-oriented host from the specialized and resource-consuming computational requirements associated with reducing image data. *Nicholas Bedworth*

Microtex Corp.

Figure 5.
Advanced peripheralized architecture in which all high-bandwidth image data is routed via special bus.



Low-Light-Level Imaging

The tremendous growth in computer-based imaging has led to applications that require imaging under very low-light-level conditions, among them medical and biological uses. Photography, despite the development of ultrahigh-speed films, does not fill the bill because most of these applications require image processing to improve contrast and definition.

The devices of choice have generally been silicon intensified target (SIT) cameras, intensified SIT (ISIT) or multiple-stage intensified vidicon cameras coupled to a microprocessor. For many applications these detectors have provided acceptable results; however, the images often are of such low intensity that vidicon cameras have proved inadequate. When the input intensity is very low, such as in medical applications, even image intensifiers and ISIT cameras can't capture an image.

The problem stems from the apparent duality of light, which, at extremely low levels, begins to behave as particles (photons) and can no longer be treated and processed as an analog phenomenon. In this case a single video frame of the TV scan, even assuming a sensitive enough detector, cannot produce a complete image, but instead generates a series of dots corresponding to individual input photons.

Some special needs

An imaging system designed to operate effectively at these ultralow-light levels requires a number of characteristics in addition to sensitivity at the single-photon level. These include a wide dynamic range to allow imaging over various intensity levels, sufficiently high spatial resolution, a high signal-to-noise ratio and real-time image acquisition and processing capabilities.

Recently, video microscopy, in which specimens are observed via a TV camera linked to a microscope, has been undergoing reevaluation in applications such as the biological examination of living cells. This approach has the advantage of bringing images to the screen in real time, permitting the observation of movement and change in specimens as they occur. In some systems digital image processing also helps solve the problems of low contrast and

mottle in the image where specimens are illuminated by low light, or emit light themselves, such as in fluorescence microscopy.

Such a system designed to take advantage of the principles of Allen video-enhanced contrast and video-intensified microscopy (VIM) has been developed by the Hamamatsu Imaging Systems Group. The device consists of a high-sensitivity detector coupled to a specially designed real-time processor employing multiple video-frame memories (Figure 1).

The key component is a two-element detector comprising a two-dimensional photon-counting tube optically coupled to a high-performance low-lag vidicon (Figure 2). The photon-counting tube consists of a photocathode, a two-stage microchannel plate (MCP) and a phosphor screen.

When an optical image focuses on the photocathode of the counting tube, photons are converted into photoelectrons, creating an image in which the number of photoelectrons is proportional to the input image. The image is then focused on the input surface of the MCP, where it may be amplified to an order of 10^6 while maintaining positional information. Next it strikes a phosphor screen, and an intensified optical image is presented to the coupled vidicon.

One of the significant advantages of the VIM system is that it may be operated in one of two modes based on the intensity of the input image. When the light intensity is sufficient, the photon-counting tube is utilized in the so-called analog mode. Here the MCP operates at a relatively low multiplication factor in which it acts as a conventional image intensifier. In the case of extremely weak intensities, where photons impinge on the photocathode in a discrete fashion, the multiplication factor of the MCP increases until it is operating in a saturation mode. This condition has been designated as the photon-counting or digital mode of operation (Figure 3).

One becomes a million

Through the multiplication process, the energy of a single incident photon may be represented by up to a million photoelectrons at the phosphor screen of the vidicon, providing a pulse-counting feature in addition

to the gray-scale imaging capability at moderate gain in the analog mode.

The signal pulses may then be manipulated by user-specified "thresholding" or "gating" to eliminate thermal electron noise pulses generated in the detection system. Furthermore, the quality of the output image can be improved by bit-slicing the input data into two, four or eight levels, as shown diagrammatically in Figure 3.

The design has resulted in an extremely wide imaging range of 10^9 to 10^9 photons/mm²/sec with a dynamic range of 1 to 10,000 in the digital mode alone. Concurrent with this sensitivity are extremely low dark-noise levels that, under normal operating conditions, rarely exceed 20 counts per second over the entire effective photocathode area of 10×10 mm. From a practical standpoint, this translates into applications ranging from photon counting to ordinary low-light-level imaging, as Figure 4 (page 96) illustrates.

However, since users often require a range above low light levels, interchangeable chalnicon, saticon and other vidicons can be used, permitting a variety of experiments on a single instrument. An additional option, an electronic zooming feature, allows for any portion of the field of view to be magnified up to ten times without shifting the object of interest to the center of the field.

The resolution characteristics of the camera head — based on the bialkali photocathode — approach those of standard SIT cameras. Clearly, spatial resolution increases with the number of photons, giving the SIT camera an advantage at normal high levels. However, this imaging system produces 18 line pairs per millimeter at the photocathode, which translates to 300-350 TV lines under normal operating conditions — close to the SIT resolution of 400 lines. The modulation transfer and the limiting resolution values, convenient ways to express tube resolution, are shown in Figures 5 and 6 (page 96).

The range of imaging detector options is shown in Figure 4. The fastest Polaroid film, or an ordinary vidicon, will produce a good image with illumination ranging from bright moonlight to starlight. The SIT and

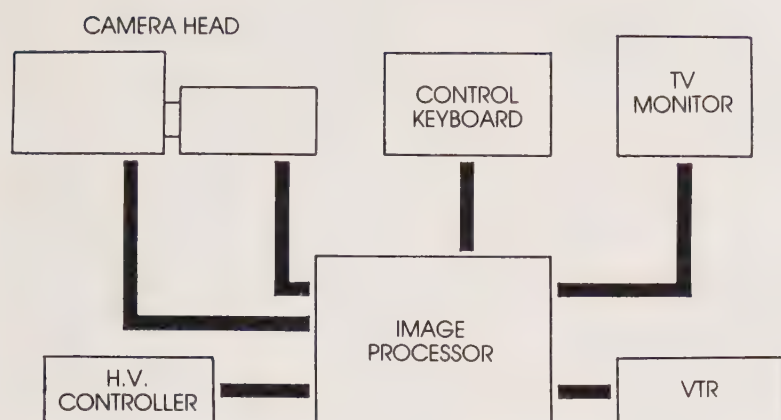


Figure 1.
Block diagram of Hamamatsu C196620 VIM system.

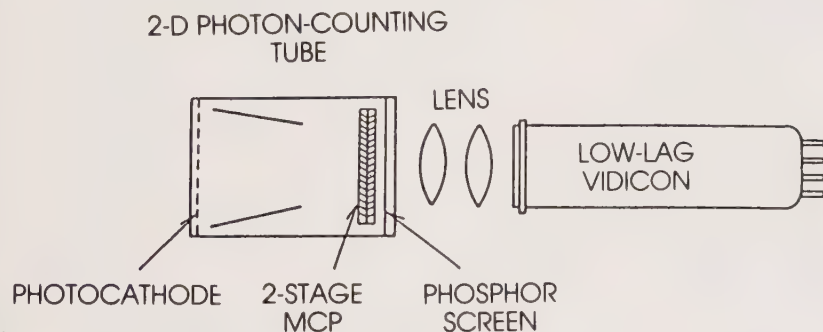


Figure 2.
Photon-counting tube and low-lag vidicon that make up the detector.

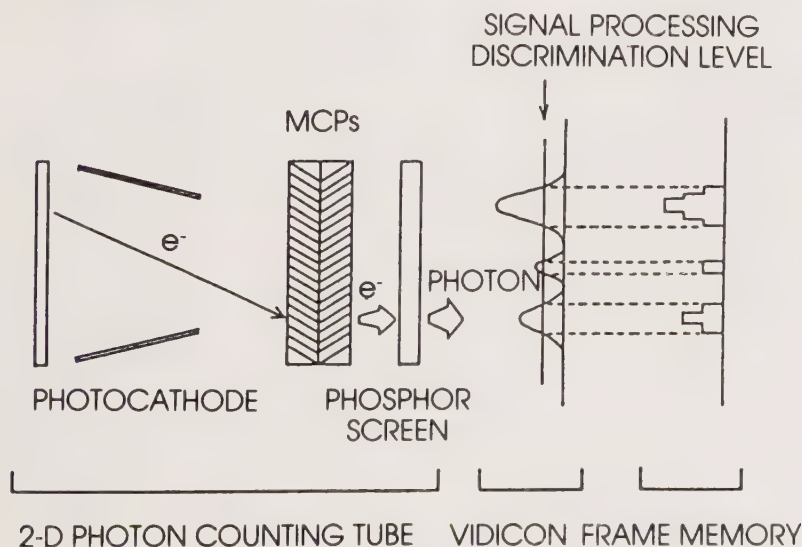


Figure 3.
Signal processing diagram for bit slicing.

ISIT vidicons are effective from moderate moonlight to levels somewhat lower than starlight. The photon-counting tube/vidicon detector produces images from moderate moonlight down to single photons — the equivalent of virtually no light at all.

A choice of intensifiers

The VIM photon-counting system offers the user a choice of image intensifiers. One employs a bialkali photocathode with a strong spectral response from 300 to 650nm. Others use multialkali (S20) and CsTe photocathodes in combination with a UV faceplate. A spectral range of from 140 to 850nm is available by selecting an intensifier and the required photocathode, and all offer a wide dynamic range from low-light to single-photon levels.

The other major component of the system is the image processor, which is designed for real-time capabilities, and contains three specially designed arithmetic logic units (ALUs) and three video frame memories for manipulation of the image in real time or off line. The frame memories are $512 \times 512 \times 16$ bits, allowing for high spatial resolution and prolonged image-integration items. This depth further allows for the generation of high-quality images at very low light levels.

In addition to simple integration, images may be acquired utilizing various averaging functions designed to render dynamic subjects accurately. Perhaps the most significant improvement in image quality is made by real-time background and dark-noise subtraction.

Following acquisition, the image may be processed by a choice of library programs, including arithmetic functions between and within frame memories, user-programmable spatial filtering of the image, gray-level transformation and pseudo-color representation.

Various quantitative features allow for image analysis, including horizontal and vertical intensity profiles, individual pixel quantification within user-specified rectilinear and free-form windows, as well as frequency histograms within any specified area of the image. The system also provides videotape storage functions and the capability to interface with host computers for additional analysis.

Applications for low-light-level imaging are many and varied, ranging from biological and astronomical applications with weak emitted light to certain industrial applications under harsh conditions.

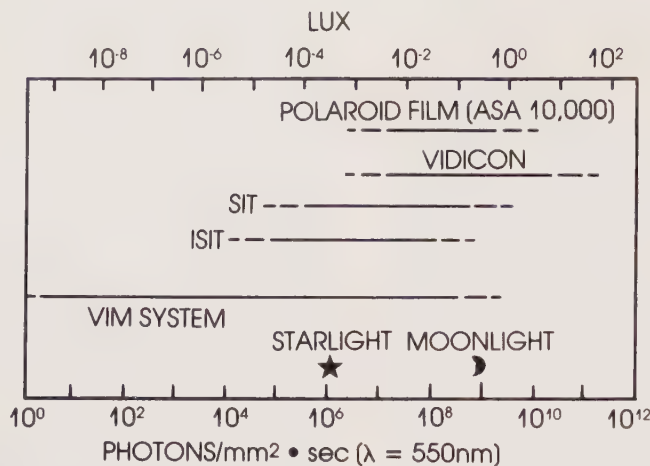


Figure 4.
Range of imaging detector options.

Figure 5.
Modulation transfer function
(digital mode).

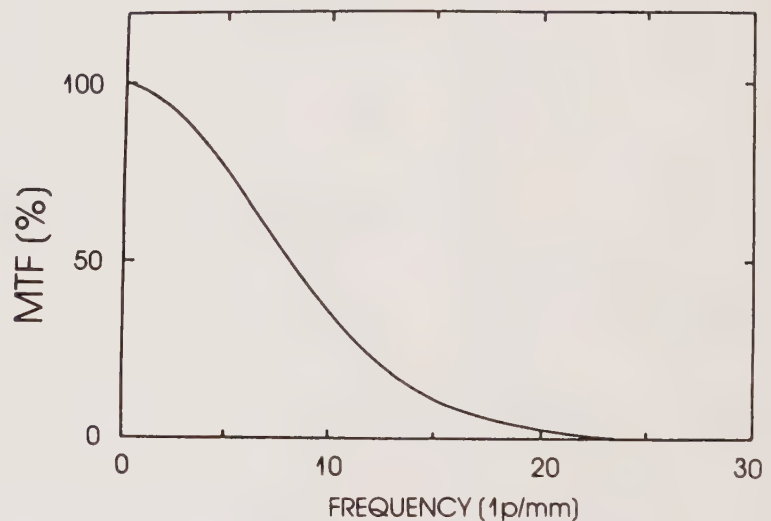
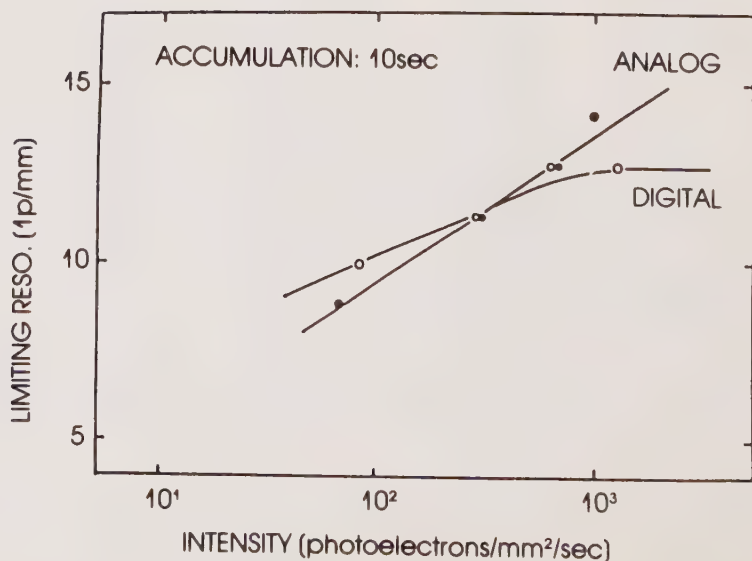


Figure 6.
Analog and digital mode
(limiting resolution).



While initial uses have involved biomedical science, a host of industrial applications is now being investigated, among them semiconductor circuit inspection, observation of the size and shape of cosmetic ingredients, astronomical observations and "instant" clinical testing.

The approach taken by the VIM system is one step toward viewing images that have never before been visible and represents an exciting branch of the technology. And, while it is much too early to predict where this technology will lead, it will surely have a hand in advancing at least some of the frontiers of science.

*Dr. Robert A. Wick
Photonic Microscopy Inc*

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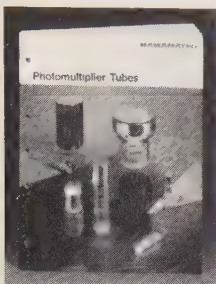
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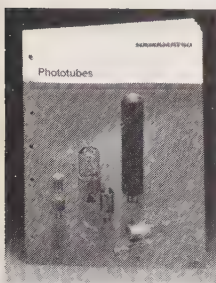
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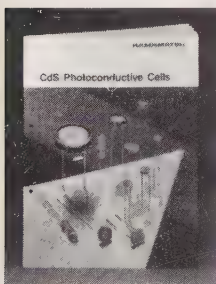
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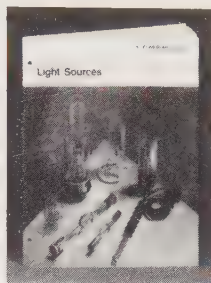


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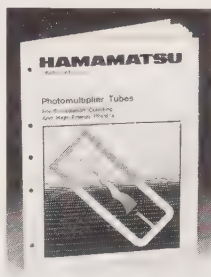


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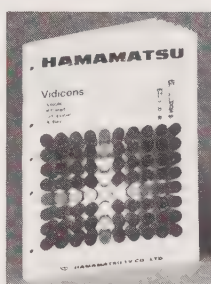
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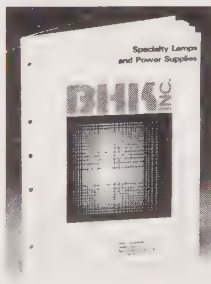
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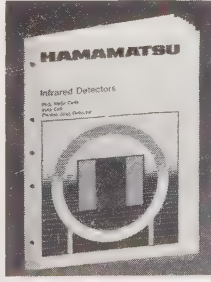
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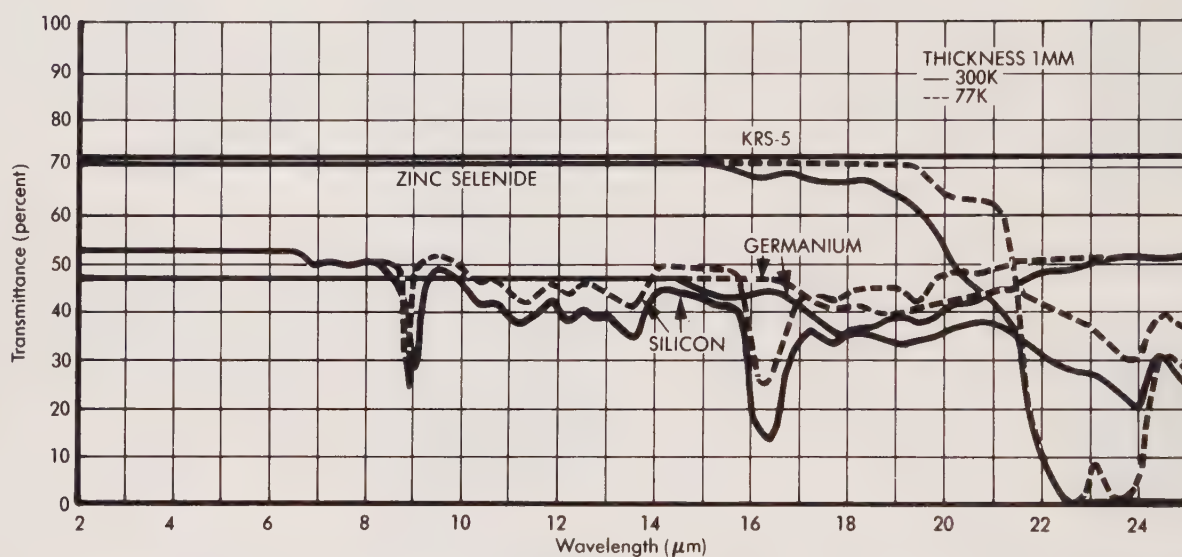
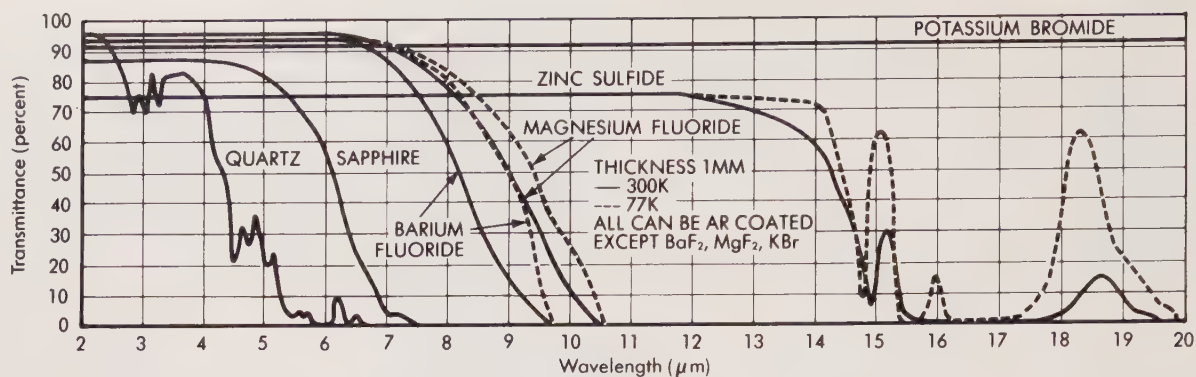
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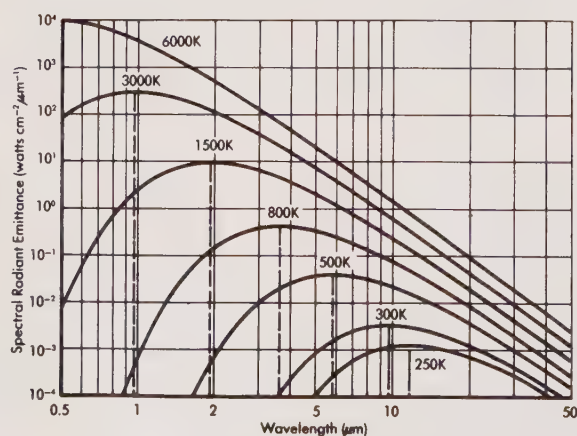
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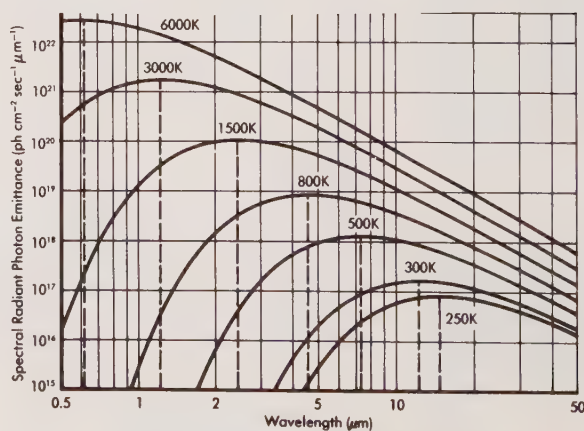
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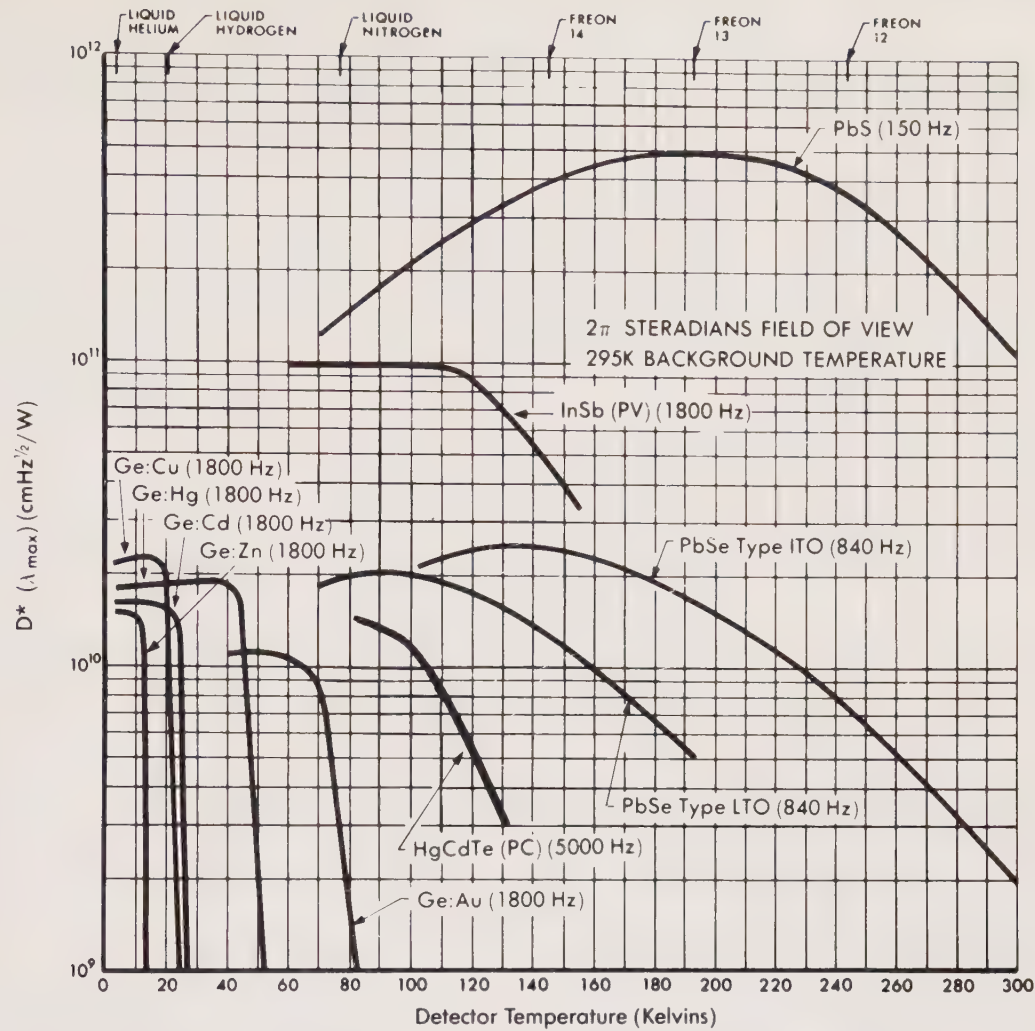
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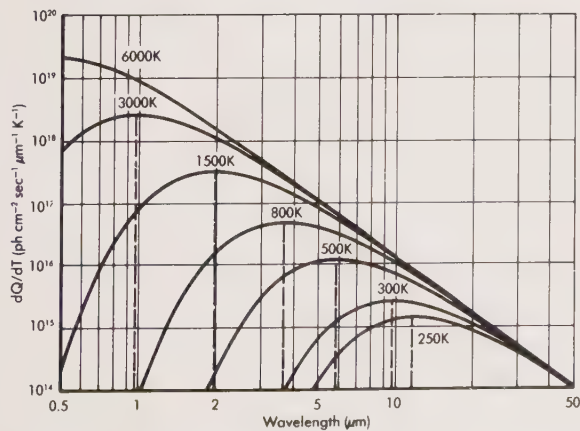
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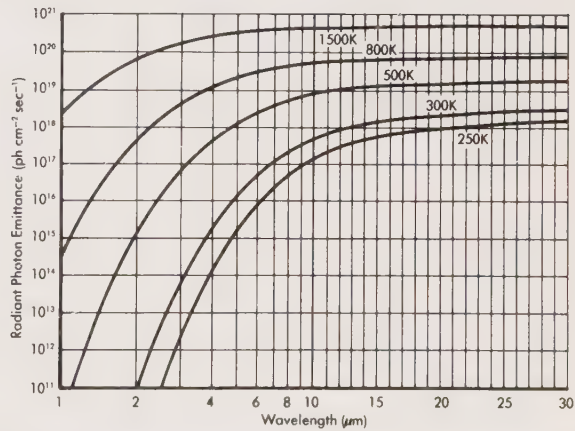
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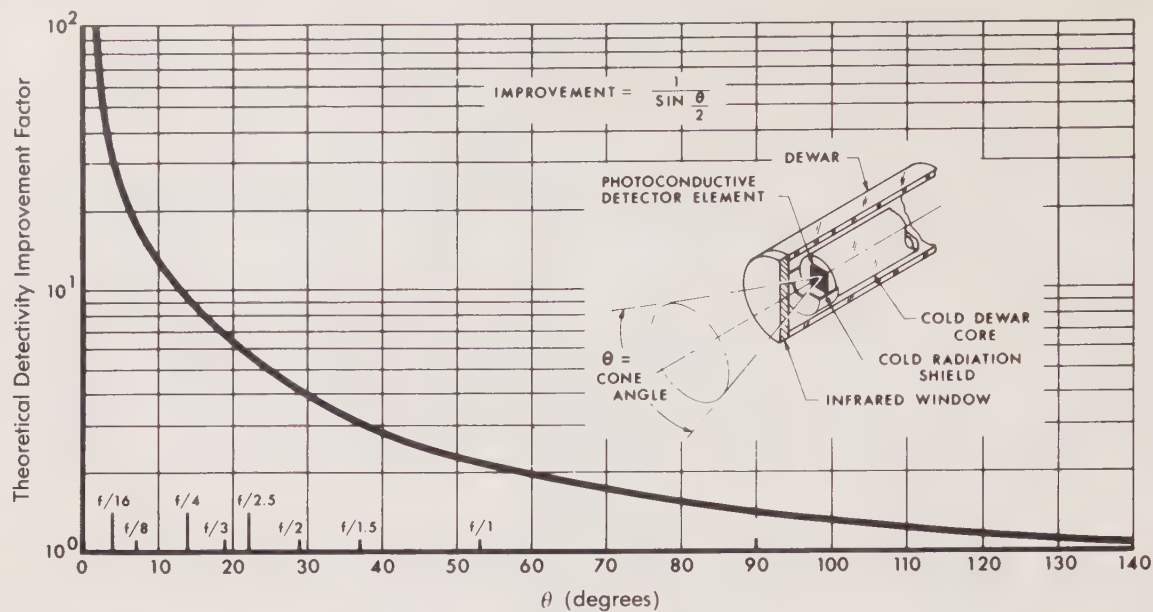
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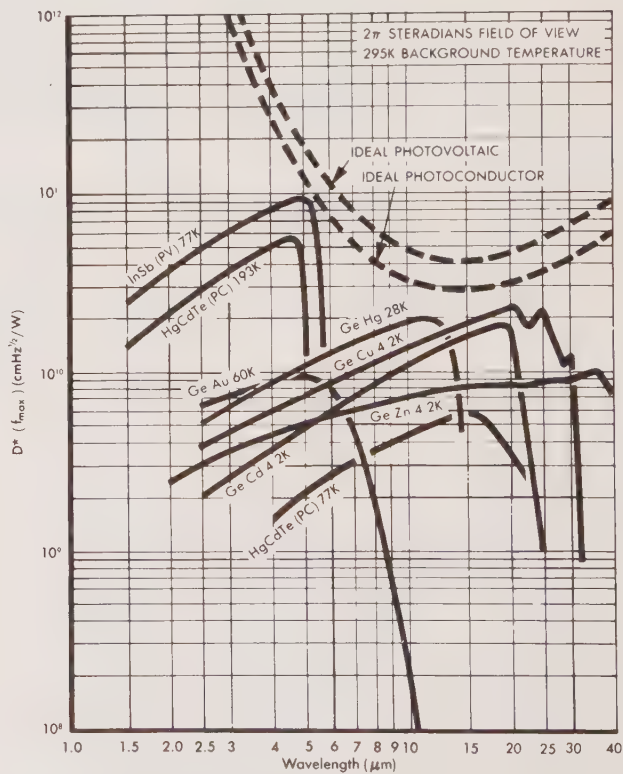
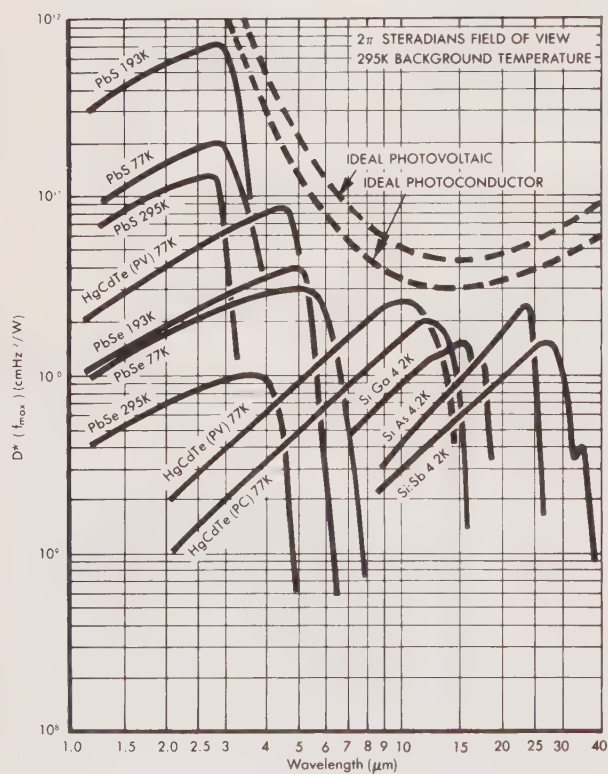
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SPECTRAL DETECTIVITIES OF VARIOUS DETECTORS (see note)

Material on this page and preceding two courtesy Santa Barbara Research Center, a subsidiary of Hughes Aircraft Company. The detectivity curves shown here, based as they are upon detectors fabricated by SBRC, are "above average," the company says, attributing the higher detectivities to a reduction in background photon flux.

Infrared Filters: Glossary, Equations, Parameters

The following is a list of terms commonly used to describe the spectral characteristics of filters:

BANDPASS FILTERS (BP) — Filters designed to transmit energy only within a selected band of wavelengths in the spectrum. These filters can be classified as narrow or wide bandpass filters, depending on the required bandwidth.

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SHORT WAVELENGTH PASS FILTERS (SWP) — Filters that transmit energy at wavelengths shorter than the cutoff. Energy at wavelengths longer than the cutoff is attenuated.

ATTENUATION REGION (OR BLOCKING) — The spectral region over which very low transmission is

required. Attenuation requirements are generally specified in percent transmission over a given spectral interval. Example: attenuation for a narrow bandpass filter centered at $2.0\mu\text{m}$ may be specified as "absolute transmission to be less than or equal to 0.1% from $0.4\mu\text{m}$ to $1.9\mu\text{m}$ and from $2.1\mu\text{m}$ to $3.0\mu\text{m}$."

BANDWIDTH (BW) — The width of a bandpass filter between specific absolute transmission points. When expressed in percent, the width is divided by the center wavelength of the band and multiplied by 100%. Example: a bandpass filter centered at $5.0\mu\text{m}$ is to provide a $1.0\mu\text{m}$ bandwidth at the 10% absolute transmission points; its bandwidth may be specified as 20% at the 10% absolute transmission points.

PEAK TRANSMISSION — The maximum transmission attained by a bandpass filter, expressed in percent. Required peak transmission of a bandpass filter may be specified as

"minimum peak transmission to be 70%." Note that peak transmission usually occurs at the center wavelength.

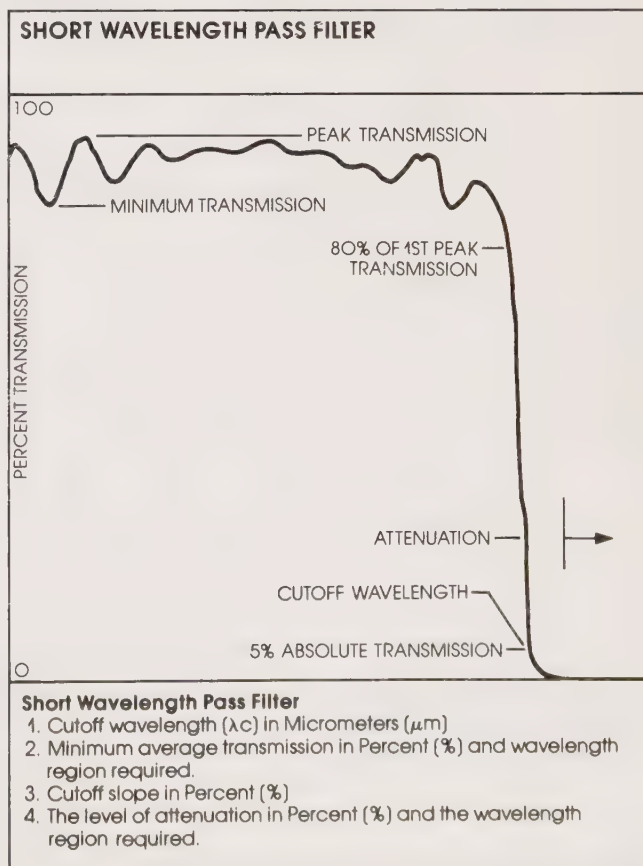
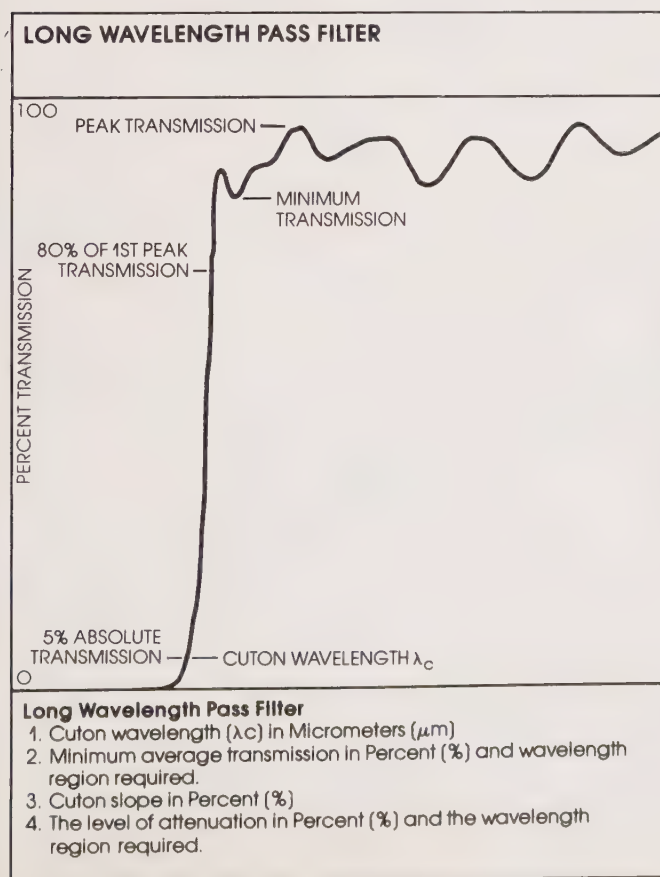
HALF-POWER POINT (HPP) — The wavelength at which a filter is transmitting one-half of its peak transmission. For a bandpass with peak transmission of 70%, the wavelengths at which it transmits 35% would be the half-power points.

CENTER WAVELENGTH (λ_0) — Center wavelength of a bandpass filter is defined

$$\frac{2\lambda_1\lambda_2}{\lambda_1 + \lambda_2}$$

where λ_1 and λ_2 are in wavelength units and denote the bandpass half-power points. This is not the simple arithmetic average because interference filters are linear or symmetrical in reciprocal wavelength, not in wavelength. Example: the center wavelength of a bandpass with half-

Filter Types



power points of $1.6\mu\text{m}$ and $1.8\mu\text{m}$ would be $1.694\mu\text{m}$ or expressed as $\lambda_0 = 1.694\mu\text{m}$.

HALF-WIDTH OR HALF-BANDWIDTH (HBW) — Bandwidth defined by specifying the half-power points as beginning and ending wavelengths.

CUTON (λ_c) — The wavelength specifying the location of the transition from a region of low transmission (attenuation) to an adjacent spectral region of high transmission. The term is often used to specify the wavelength location of a long wavelength pass filter. The wavelength of the 5% absolute transmission is commonly used as the cuton wavelength.

CUTOFF (λ_c) — The wavelength specifying the location of the transition from a region of high transmission to a region of low transmission (attenuation). This term is often used for specifying wavelength location of a short wavelength pass filter. As in the case for "cuton," cutoff wavelength commonly refers to the 5% absolute transmission.

(Continued)

Equations

1) Single surface, normal incidence in air

$$R = \frac{(1 - N)^2}{(1 + N)^2}$$

2) Two surfaces with an internal transmittance K

$$T_{1,2} = \frac{T_1 T_2 K}{1 - K^2 R_1 R_2}$$

Where R = Reflection

T = Transmission

N = Index of Refraction

$$T = \frac{4N}{(N + 1)^2}$$

For K = 1 $T_1 = T_2$ $R_1 = R_2$

$$T = \frac{2N}{N^2 + 1}$$

$$R = \frac{(N - 1)^2}{N^2 + 1}$$

3) Critical Angle (I_C)

$$I_C = \arcsin \frac{N^1}{N}$$

4) Brewster's Angle (I_B)

$$I_B = \arcsin \frac{N^1}{N}$$

6) Numerical Aperture = $N^1 \sin U^1$
where N^1 = index of refraction of medium where image lies, and U^1 is the half cone angle.

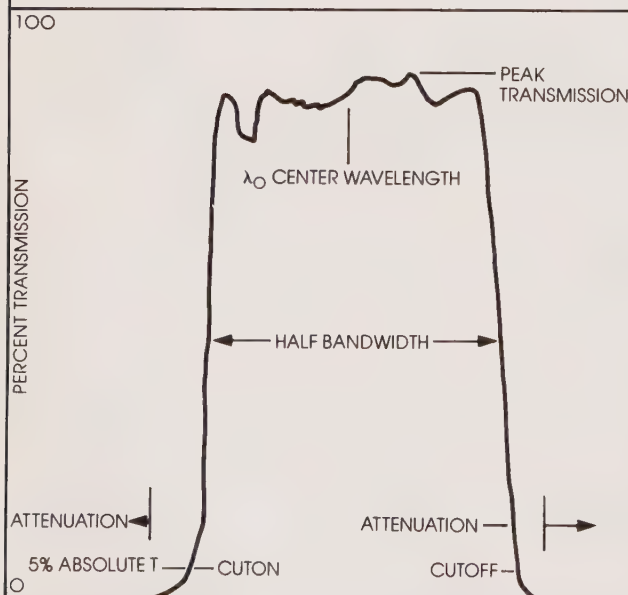
7) Airy Disc Diameter = $2.44\lambda F^\#$

5) f-number ($F^\#$) = $\frac{\text{Focal Length}}{\text{Clear Aperture}}$

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Filter Types

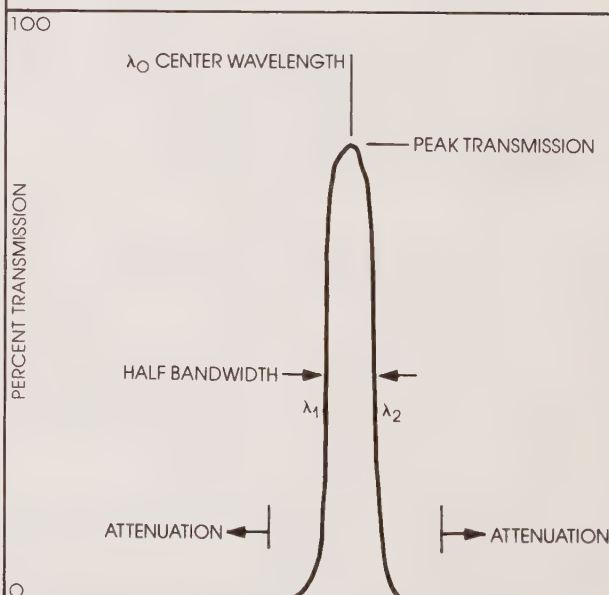
WIDE BANDPASS FILTER



Wide Bandpass Filter

1. Cuton and Cutoff Wavelength (λ_c) in Micrometers (μm)
2. Minimum average transmission in Percent (%) and the wavelength region required.

NARROW BANDPASS FILTER



Narrow Bandpass Filter

1. Center Wavelength (λ_0) in Micrometers (μm)
2. Minimum peak transmission in Percent (%)
3. Half Bandwidth in Percent (%) of the center wavelength
4. The level of attenuation in Percent (%) and the wavelength region required.

SLOPE — CUTON OR CUTOFF —

The wavelength interval required to traverse the distance from the 5% transmission cuton or cutoff point to the 80% of peak transmission cuton or cutoff point. Often specified in percent as follows:

$$\begin{aligned} \% \text{ Slope} = & \\ & \frac{\lambda \text{ 80\% of Peak} - \lambda \text{ 5\% Absolute}}{\lambda \text{ 5\% Absolute}} \\ & \times 100 (\%) \end{aligned}$$

Note that λ 5% is the wavelength of the 5% absolute transmission point, whereas λ 80% is the wavelength at which the filter is transmitting 80% of the transmission of the first peak adjacent to the cuton or cutoff.

AVERAGE TRANSMISSION —

Average transmission is given in percent over a spectral interval. This term is commonly used to specify transmission characteristics of long wavelength pass, short wavelength pass, and wide bandpass filters. Typically, the specification might read: "minimum average transmission between $3\mu\text{m}$ and $5\mu\text{m}$ to be equal to or greater than 80%."

How to specify optical performance of individual filter types

Substrate Type**Substrate Physical Dimensions**

- a. Length, width, or diameter
- b. Thickness
- c. Surface Quality (MIL-F-48616)
- d. Parallelism of surfaces
- e. Clear aperture

Filter use conditions

- a. Angle of incidence or cone angle of radiant energy
- b. Filter operating temperature

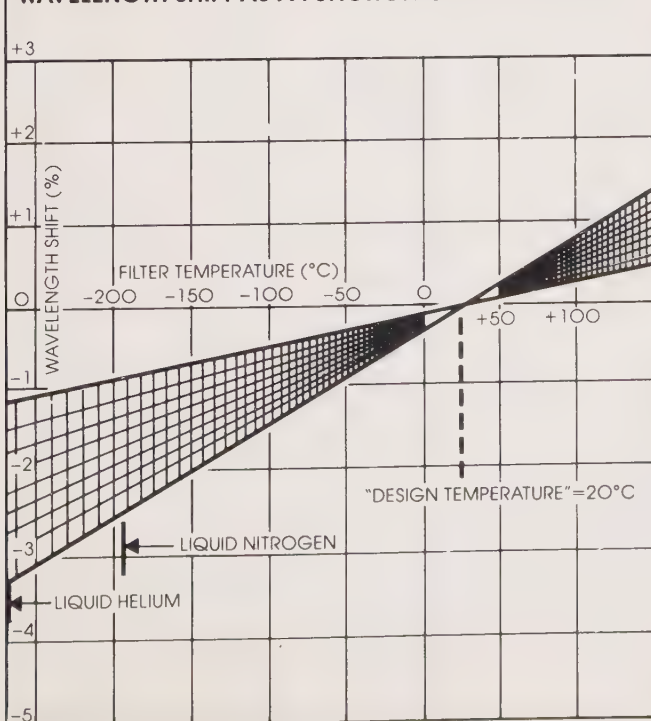
Environmental requirements per MIL-F-48616

- a. Adhesion — 3.4.2.1.1
- b. Humidity — 3.4.2.1.2
- c. Moderate Abrasion — 3.4.2.1.3
- d. Temperature — 3.4.2.2.1
- e. Solubility and cleanability — 3.4.2.2.2
- f. Operational Durability — 3.4.2.3 (when required)
 1. Severe Abrasion — 3.4.2.3.1
 2. Salt Solubility — 3.4.2.3.2
 3. Water Solubility — 3.4.2.3.3
 4. Salt Spray and Salt Fog — 3.4.2.3.4

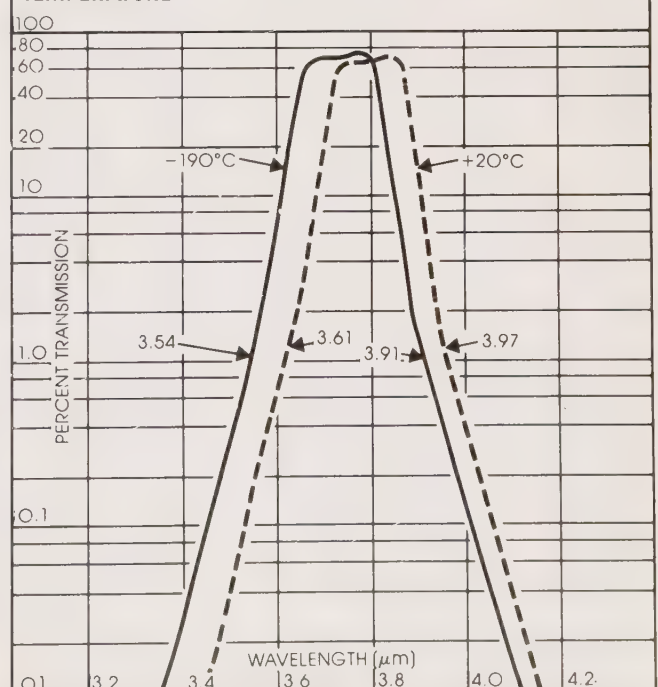
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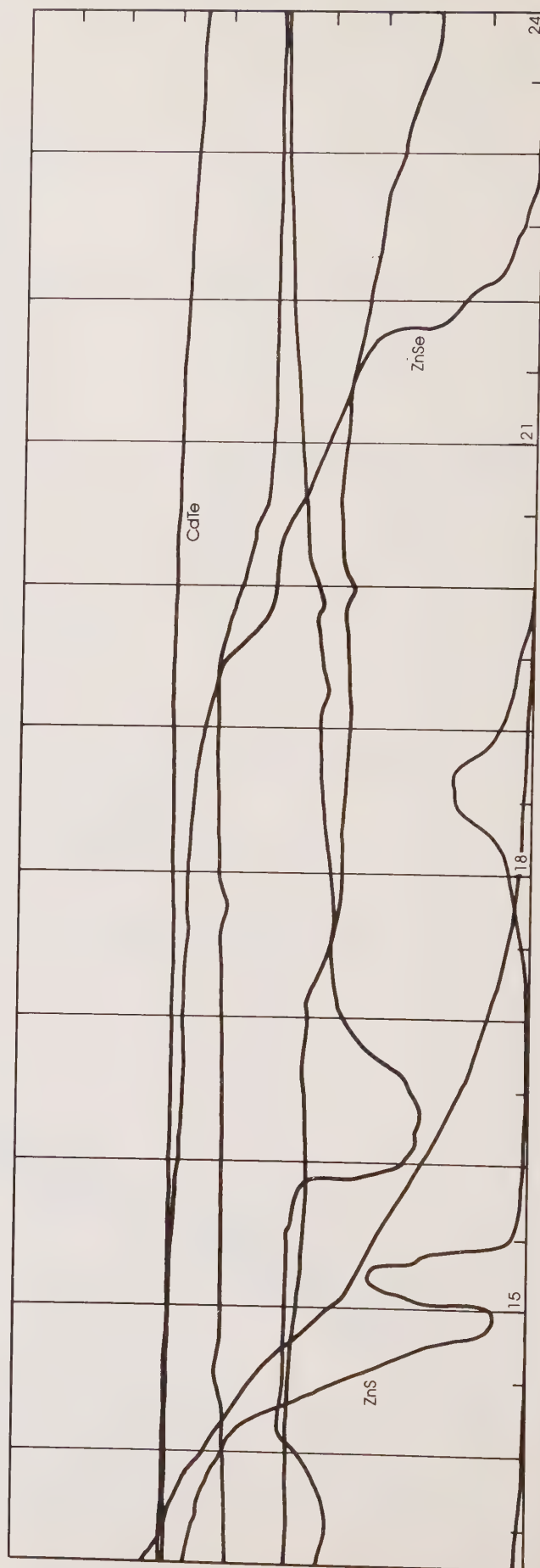
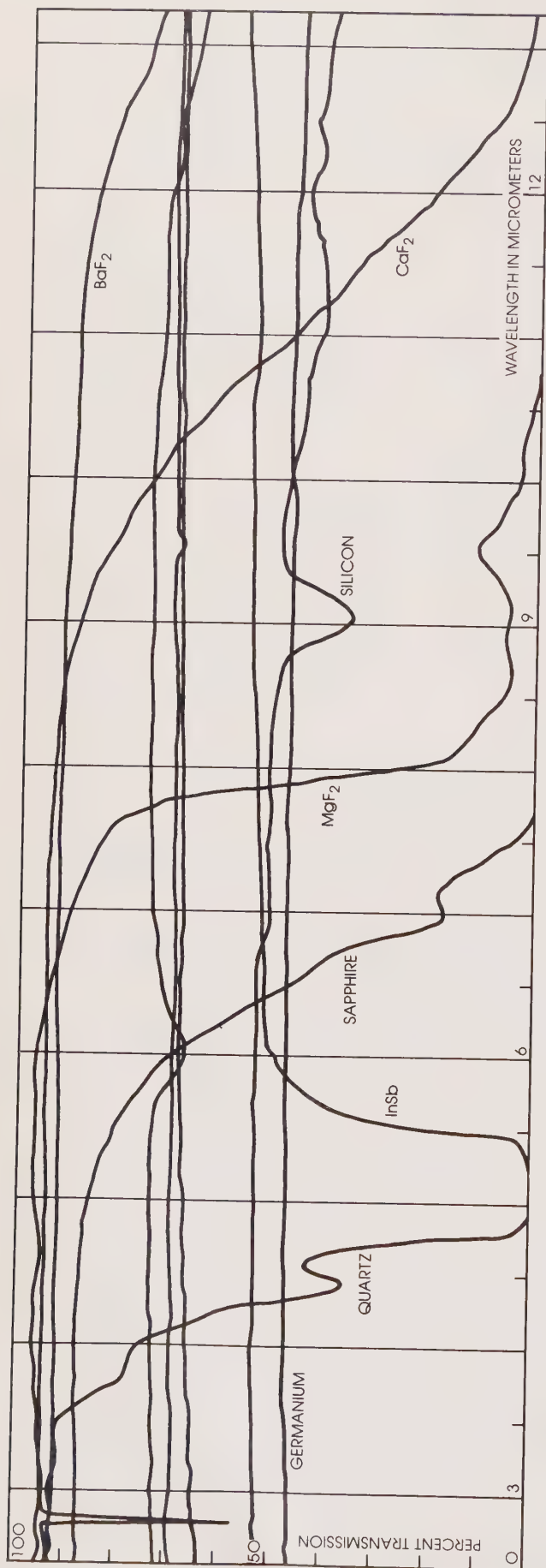
IR Filters: Temperature Effects

WAVELENGTH SHIFT AS A FUNCTION OF TEMPERATURE



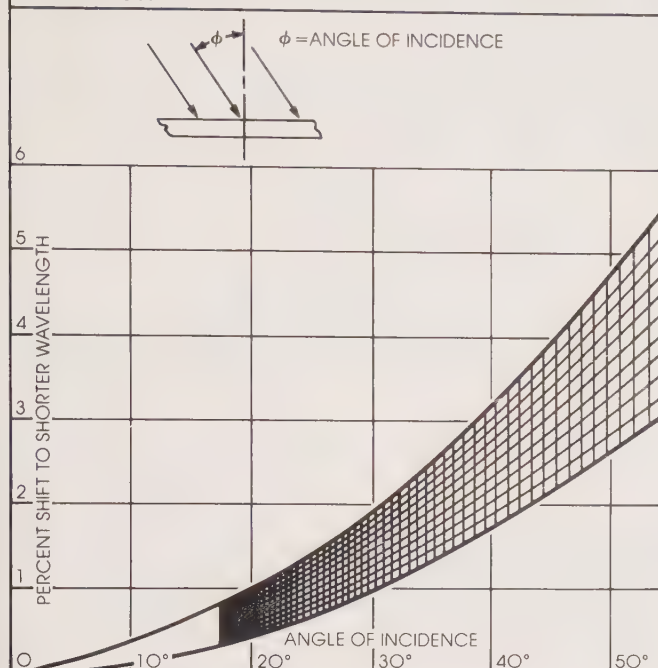
MEASURED VARIATION OF A TYPICAL FILTER WITH TEMPERATURE



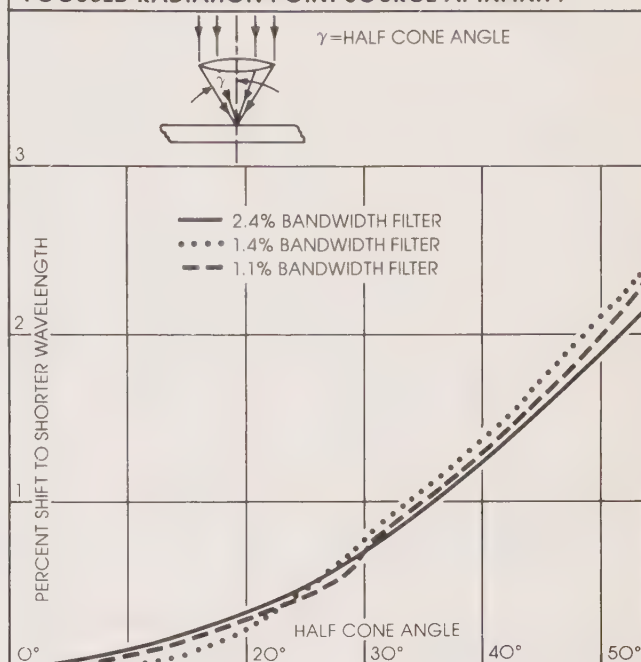


IR Filters: Angle Effects

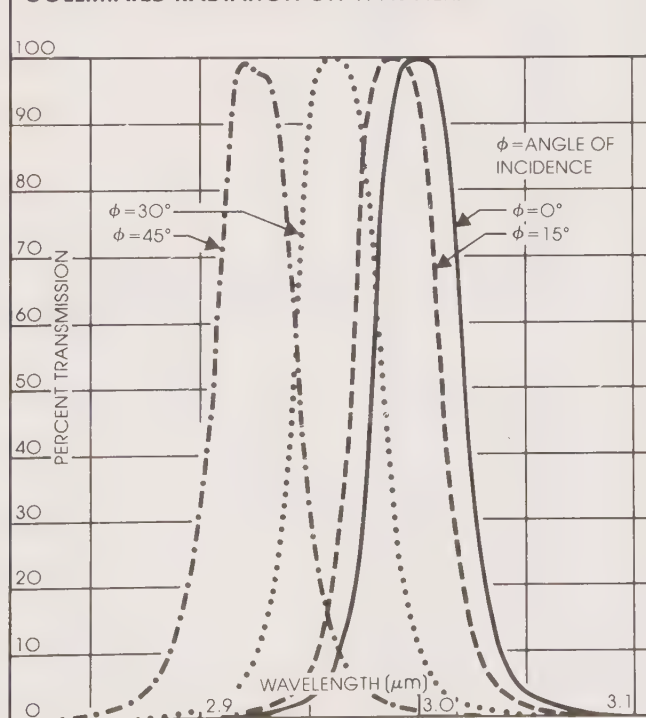
WAVELENGTH SHIFT OF INTERFERENCE FILTERS AS A FUNCTION OF ANGLE OF INCIDENCE COLLIMATED RADIATION



WAVELENGTH SHIFT OF THREE NARROW BANDPASS FILTERS AS A FUNCTION OF HALF CONE ANGLE FOCUSED RADIATION-POINT SOURCE AT INFINITY

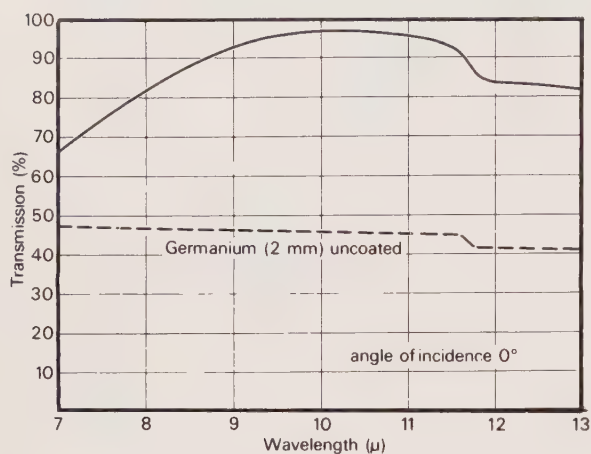


COLLIMATED RADIATION ON 1.4% FILTER



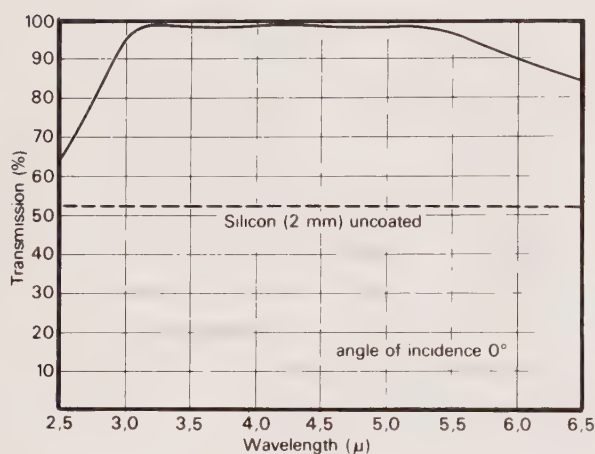
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Antireflection Coatings for the Infrared



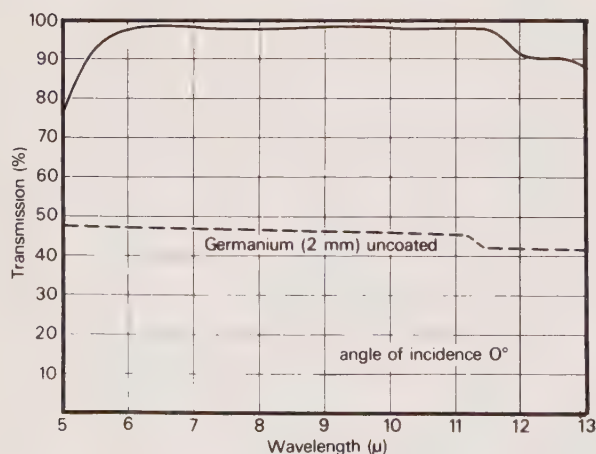
SINGLE LAYER COATINGS

Single-layer coatings are generally used where high transmission over a relatively narrow wavelength interval is required. Peak transmission can be set at any desired wavelength up to 15μ .



MULTILAYER AR COATING FOR THE IR

Multilayer AR coatings are used where transmission should be kept uniformly high over a wide range. On silicon: wavelength range $3\text{--}5\mu$.



MULTILAYER AR COATING FOR THE IR

See above. On germanium: wavelength range $7\text{--}11\mu$.

SOURCE: BALZERS CORP.

Infrared Detectors

Solid-State Detectors

COMPANY	MATERIAL	PC	PV	OTHER	SPECTRAL RANGE (μm)	D* ($\text{cmHz}^{1/2}/\text{W}$)	NEP ($\text{WHz}^{-1/2}$)	RESPONSIVITY (A/W OR V/W AT λ) (ROOM = 22°C)	OPERATING TEMPERATURE/ COOLING METHOD	RISE TIME (nsec)	ACTIVE AREA (mm^2)	PACKAGE TYPES	PRICE
AG Electro Optics Ltd.	HgCdTe	•			5-12	2×10^{10}	—	8 A/W^{-1} (10.6 μm)	LN_2 , Joule Thomson	<10	1.0, .0625, .01, .0025	Dewar, MWR	\$3200+
Amperex Electronic Corp.		•	•		1-70	3×10^8	6×10^{-10}	640 V/W^{-1} , 750 V/W^{-1}	-55°C - +85°C Air-cooled	—	2	TO5, SOT49H	\$225-\$975
Antel Optonics	Ge Pin				5-1.8	—	1×10^{-10}	$.25 \text{ A/W}$ (1.5 μm)	Room	.05	.01	Custom microwave pkg., TO cans	\$1795
	Ge APD				5-1.8	—	1×10^{-10}	$.2 \text{ A/W}$ (1.5 μm)	Room	.09	.03	Microwave, TO cans	\$2795
Boston Electronics	HgCdTe		•		2-12	$\geq 5 \times 10^5$	—	$\geq 5 \text{ mV/W}$ (10.6 μm)	Room	.2	1 x 1	34 x 27.5 x 19mm	\$2220
	HgCdTe	•			2-12	$\geq 1 \times 10^6$	—	$\geq -10 \text{ mV/W}$ (10.6 μm)	Room	1.0	1 x 1	13 x 42mm	\$1130
Centronic Inc.	Si	•			4-1.1, 7-1.1	—	—	$.5 \text{ A/W}$ (900nm)	-20°C - +70°C	50, 300	1, 9	Epoxy, TO5, TO18	\$90-\$2 Qty. 1K
	Ge	•			6-1.9	—	3.3×10^{-12}	$.7 \text{ A/W}$ (.5 μm)	-20°C - +75°C	10	1, 3	TO8, TO18	\$75+ Qty. 1K
	Si	•			4-1.15	—	7×10^{-14}	$.45 \text{ A/W}$ (1.06 μm)	-25°C - +75°C	20	1, 5, 50, 100, 200, 300	TO5, TO8, TO18, special pkgs.	\$32 Qty. 100
Cincinnati Electronics Corp.	InSb	•			1-5.5	1×10^{11}	10^{-16} , 10^{-8}	3.2 A/W (5.0 μm)	2-120K LHe, LN_2 , cryostat, passive radiator	<1000	1.86×10^{-3} , 20	CF	\$1000+
Clairex Electronics	Si	•	•		4-1.1	—	—	$.50 \text{ A/W}$ (850nm)	-40°C - +100°C	5000	.10-25	Chips, TO5 TO18, Flat Pak, custom plastic	CF
Edinburgh Inst.	Ge		•		9-11	5×10^{12}	3.5×10^{-3}	2	Room	<1	78.5	BNC	CF
EG&G E-O	Si	•	•		2-1.1	—	3×10^{-13} (1.06)	$.6 \text{ A/W}$ (.9 μm)	-55°-125°C	1-10	—	TO5, TO8, TO18, TO36	\$15-\$325
Electro-Optical Systems Specialists	HgCdTe	•			1-20	10^{11}	$<10^{-13}$	10^5 V/W	Room, TE cooled, Liquid nitrogen	.3 μm , 10	2	Hermetic headers, vacuum dewars	\$1500+
	HgCdTe	•	•		1-5	10^{11}	$<10^{-13}$	2.7 A/W	TE cooled, Liquid nitrogen	1	2-7	Hermetic TO-style, vacuum dewars	\$1200+
	Ge & InGaAs	•			1-1.8	$>10^{11}$	$<10^{-14}$	0.7 A/W	Room, TE cooled, Liquid nitrogen	1	5	TO headers, vacuum dewars	\$60+
Ford Aerospace Comm. Corp.	HgCdTe	•			10-6	10^{10}	$<10^{-19}$	$.5 \text{ A/W}$ (10.6 μm)	77K	1	6×10^{-3} , 6×10^{-2}	Metal/glass dewars	CF

CF = consult factory

COMPANY	MATERIAL	PC	PV	OTHER	SPECTRAL RANGE (μm)	D* ($\text{cmHz}^{1/2}/\text{W}$)	NEP ($\text{WHz}^{-1/2}$)	RESPONSIVITY (A/W OR V/W AT λ) (ROOM = 22°C)	OPERATING TEMPERATURE/ COOLING METHOD	RISE TIME (nsec)	ACTIVE AREA (mm^2)	PACKAGE TYPES	PRICE
Ford Aerospace (cont.)	HgCdTe	●			8-12	3×10^{10}	3×10^{-11}	100K V/W (11 μm)	77K	50	6×10^{-3} -25	Metal/glass dewars	CF
	HgCdTe	●			3-5.5	10^{11}	10^{-12}	100K V/W (5 μm)	77K & 195K	150	6×10^{-3} -25	Metal/glass dewars (77K), Thermoelec. cooler (195K)	CF
	HgCdTe	●			8-11	3×10^{10}	3×10^{-11}	5 A/W (10 μm)	77K	500	6×10^{-3} -1.0	Metal/glass dewars	CF
	HgCdTe	●			3-5	10^{11}	10^{-12}	2.5A/W (5 μm)	77K	500	6×10^{-3} -1.0	Metal/glass dewars	CF
	InSb	●			3-5.5	10^{11}	10^{-12}	3.5A/W (5 μm)	77K	500	6×10^{-3} -16	Metal glass dewars	CF
	Ge	●			1.0-1.8	10^{12}	10^{-13}	1.0A/W (1.55 μm)	300K or -25°C	1×10^{-4}	6×10^{-3} -100	Coax, pill, TO5, TO8, TO18, Flat Paks	CF
Germanium Power Devices	Ge	●	●		.5-1.8	—	16×10^{-12}	.5A/W	-30 -75°C Two stage cooler	200	19.625	TO8	\$450 Qty. 675
	Ge	●	●		.5-1.8	—	16×10^{-12}	.5A/W	-20 -+75°C	200	19.625	TO8	\$102 Qty. 150
	Ge	●	●		.5-1.8	—	9×10^{-12}	.7A/W	-20 -+75°C	100	7.065	TO8	\$102 Qty. 150
	Ge	●	●		.5-1.8	—	6.4×10^{-12}	.7A/W	-20 -+75°C	45	3.14	TO5	\$85 Qty. 130
	Ge	●	●		.5-1.8	—	3.3×10^{-12}	.7A/W	-20 -+75°C	10	.785	TO5, TO18	\$65 Qty. 100
	Ge	●	●		.5-1.8	—	$.8 \times 10^{-12}$	.7A/W	-20 -+75°C	1	.07	TO18	\$50 Qty. 75
	Ge	●	●		.5-1.8	—	$.3 \times 10^{-12}$	.7A/W	-20 -+75°C	.1	.00785	TO18	\$95 Qty. 145
Hamamatsu	Si	●	●		.190-1.15	2×10^{12} 6×10^{13}	2×10^{-14} 6×10^{-15}	.2-.5A/W	Room	1-10	.12-98	TO5, TO8 TO18 ceramic	CF
Honeywell Inc.	HgCdTe	●			8-14	2×10^{10}	3×10^{-20}	3-7A/W	77K TE cooled, Liquid nitrogen	1	125x125 - 250x250	LN ₂ stainless steel dewar	CF
Infrared Associates Inc.	HgCdTe	●			2-25	3×10^{10}	—	—	Liquid nitrogen Joule Thomson cryostats	<500	3x3, 4x4, 5x5	Metal/glass dewars	CF
	HgCdTe & InSb	●	●		1-14	1×10^{11} 1.5×10^{10}	—	—	Liquid nitrogen Joule Thomson cryostats	<1 <400	1x1, 2x2, 2.5x2.5	Metal/glass dewars	CF
	HgCdTe	●			2-25	$>4 \times 10^3$	—	—	Liquid nitrogen Joule Thomson cryostats	100	.05x.05- 2.5x2.5	Metal/glass dewars	CF
	HgCdTe	●			2-12	$\geq 1 \times 10^{10}$	—	—	Liquid nitrogen Joule Thomson cryostats	<50	.025x.025- 1x1	Metal/glass dewars	CF
	HgCdTe	●			2-13	$>2 \times 10^{10}$	—	—	Liquid nitrogen Joule Thomson cryostats	300	2x2.5x6	Metal/glass dewars	CF
	HgCdTe	●			2-14	$>4 \times 10^{10}$	—	—	Liquid nitrogen Joule Thomson cryostats	400	.025x.025- 2.5x2.5	Metal/glass dewars	CF
	HgCdTe	●			2-18	$\geq 2 \times 10^{10}$	—	—	Liquid nitrogen Joule Thomson cryostats	200	.05x.05- 1x1	Metal/glass dewars	CF
	HgCdTe	●			2-20	1.5×10^{10}	—	—	Liquid nitrogen Joule Thomson cryostats	<200	.05x.05- 1x1	Metal/glass dewars	CF
	HgCdTe	●			2-25	$>1 \times 10^{10}$	—	—	Liquid nitrogen Joule Thomson cryostats	<100	.05x.05- 1x1	Metal/glass dewars	CF
	HgCdTe	●			2-25	$>1 \times 10^{10}$	—	—	Liquid nitrogen Joule Thomson cryostats	<100	.05x.05- 1x1	Metal/glass dewars	CF

CF = consult factory

COMPANY	MATERIAL	PC	PV	OTHER	SPECTRAL RANGE (μm)	D* ($\text{cmHz}^{1/2}/\text{W}$)	NEP ($\text{WHz}^{-1/2}$)	RESPONSIVITY (A/W OR V/W AT λ) (ROOM = 22°C)	OPERATING TEMPERATURE/ COOLING METHOD	RISE TIME (nsec)	ACTIVE AREA (mm^2)	PACKAGE TYPES	PRICE
Infrared Assoc. (cont.)	InSb	●			1-5	$>1 \times 10^{11}$	—	$>2.5\text{A/W}$	Liquid nitrogen Joule Thomson cryostats	<1000	.25, .50, 1.0, 2.0, 2.5, 3.0, 4.0, 7.0	Metal/glass dewars	CF
	HgCdTe	●			8-12	$>2 \times 10^{10}$	—	$<8\text{A/W}$	Liquid nitrogen Joule Thomson cryostats	<3	.1 x .1 .25 x .25, 1 diam.	Metal/glass dewars	CF
	HgCdTe	●			2-11	4×10^8	—	$>1\text{V/W}$	TE cooled	<10	1 x 1, 2 x 2	—	CF
	Ge	●			1-18	$>8 \times 10^{10}$	—	—	TE cooled	—	.25, .5, 1, 2, 3, 5	TO5, TO8, TO18, BNC	CF
Infrared Industries	PbSe & PbS	●			1-5, 1-3, 5	Varies	Varies	Varies	TE cooled, cryogenic	Varies	Varies	TO-type, metal/glass dewar	\$20-up
	Si	●			.2-1.13	Varies	Varies	Varies	Room	50-300	Varies	TO-type	\$20-up
Infrared Laboratories	InSb	●			300-7500	—	$<7.5 \times 10^{13}$	$6 \times 10^3 \text{V/W}$ (1000)	4.2 K helium	0-600kHz	5.0 x 5.0	Integrating cavity	\$2150
	Ge:Ga	●			30-120	—	1.5×10^{16}	1.5A/W	4.2K helium	10-100	2 x 2	Custom	\$3200
	Si:Ga	●			6-18	—	10^{16}	1.5A/W	4.2K helium	.1-5	1.0 x 1.0	Custom	\$3200
Instrument Technology Ltd.	Ge	●			.8-1.8	—	—	.7 (1.5 μm)	TE cooled	—	1, 3, 5	TO8, TO37, TO66	CF
	InGaAs	●			1-1.8	—	—	.8 (1.55 μm)	Room	Varies	.1, .5, 1, 2	TO18 header	CF
	InSb	●			1-5.5	.8- 4×10^{11}	—	2.8A/W (5.1 μm)	77K	Varies	.25-7	Side or down-looking metal dewar	CF
	HgCdTe	●			2-20	5×10^9 - 1×10^{11}	—	Varies (10^2 - 10^5)	77K	—	.05-2	Side or down-looking metal dewar	CF
	Ge	●			.8-1.8	—	—	.7A/W (1.5 μm)	Room	Varies	.3-5	TO5, TO8, TO18 headers	CF
Judson Infrared	HgCdTe	●			2-5.5	.5- 1.5×10^{11}	—	—	77K	400-6000	.01-4	Metal/glass dewar	CF
	HgCdTe	●			2-5.5	4×10^{10}	—	—	-25°C TE cooled	<5000	.01-4	—	CF
	HgCdTe	●			2-14	$3-6 \times 10^{10}$	—	10^3 - 10^5V/W	77K	200-1000	.01-4	Metal/glass dewar	CF
	HgCdTe	●			2-22	$.5-2 \times 10^{10}$	—	—	77K	100-600	.01-4	Metal/glass dewar	CF
	HgCdTe	●			10.6	2.8×10^8	—	—	200K TE cooled	10-50	.01-4	—	CF
	Ge	●			.8-1.5	4×10^{12}	—	$>.6\text{A/W}$ (1.3 μm)	77K	1000	.05-20	Metal/glass dewar	CF
	InAs	●			1.0-3.5	3×10^9	—	1.0A/W (3.4 μm)	Room	50-200	.05-3.0	TO5, TO18, BNC	CF
	Ge	●			.8-1.7	8×10^{11}	—	.6A/W (1.3 μm)	-25°C TE cooled	1000	.05-20	—	CF
	Ge	●			.8-1.8	2×10^{11}	—	$>.6\text{A/W}$ (1.3 μm)	Room	3.0 - 1000	.05-130	TO5, TO8, TO18, 1" TO, BNC	CF
	InSb	●			1.0-5.5	$>1 \times 10^{11}$	—	$>2.0\text{A/W}$ (5.0 μm)	77K	100	.01-38	Metal/glass dewar	CF
	InGaAs	●			.8-1.8	6×10^{11}	—	.7A/W (1.3 μm)	Room	2	.01-3	TO5, TO185	CF
Lasermetrics, Inc.	Si Pin				—	—	1.3×10^{-14}	500A/W (800 μm)	Room	.15	1.0	—	\$950

CF = consult factory

COMPANY	MATERIAL	PC	PV	OTHER	SPECTRAL RANGE (μm)	D* ($\text{cmHz}^{1/2}/\text{W}$)	NEP ($\text{WHz}^{-1/2}$)	RESPONSIVITY (A/W OR V/W AT λ) (ROOM = 22°C)	OPERATING TEMPERATURE/ COOLING METHOD	RISE TIME (nsec)	ACTIVE AREA (mm^2)	PACKAGE TYPES	PRICE
Macam Photometrics Ltd.	Ge	•	•		.8-1.8	—	15×10^{-12}	.7A/W (1.5 μm)	-10 - +50°C	—	1-5	—	—
New England Photoconductor	PbSe	•			1-6	1.1×10^{10}	—	.004-.4A/W	Room, TE cooled	3-100	.0125-10	TO3, TO5, TO8 dewars	\$32-750
	PbS	•			1-3.4	2.40×10^{10}	—	.5-10A/W	77K, TE cooled	50-500	.012-10	TO3, TO5, TO8 dewars	\$28-750
New England Research Ctr.	HgCdTe	•	•		3-5, 8-12, 8-25	1×10^{11}	—	4A/W	77K, Joule Thomson, TE cooled	10	10 x 10-4 x 4	Dewar	CF
Optoelectronics	PbS	•			1.8-2.8	7×10^{10}	—	0.5-4A/W	Room	—	—	Dewar	\$40-10,000
	PbSe	•			2-5	$\geq 1 \times 10^{10}$	—	.004-0.3A/W	Room	—	—	Dewar	\$48-10,000
Opto-Electronics	Ge	•	•		.5-1.8	$\geq 3 \times 10^{-11} \leq 3 \times 10^{-13}$	—	.7A/W (1.5 μm)	-50°C, TE cooled	Area dependent.	.01-4	Window or fiber pigtailed, vacuum	\$3800+
Ortel Corp.	GaAs	•	•		.7-.9	—	2.7×10^{14}	.35A/W	Room	.05	50	—	\$925
	GaAs	•	•		.7-.9	—	8.6×10^{-14}	.35A/W	Room	.025	25	—	\$2400
	GaAs	•	•		.7-.9	—	6.7×10^{-14}	.45A/W	Room	.025	25	—	\$1950
	GaAs	•	•		.7-.9	—	2.1×10^{-14}	.45A/W	—	.05	50	—	\$475
Philips Electronic Components & Material Division	HgCdTe				3-5	1.5×10^{10}	—	$1.2 \times 10^4 \text{ V/W}$	195K, TE cooled	—	—	R124, custom	CF
	HgCdTe				3-5	—	—	—	195K, TE cooled	—	—	R124, R132, custom	CF
Quantrad Corp.	Si	•	•		3-1.1	—	.15-6	.5A/W (9 μm)	Room	10-300	3-800	Varies	CF
QEI	InSb	•			200-7500	—	$< .5 \times 10^{12}$	5000V/W	Liquid helium	500	5 x 5	—	CF
	Ge	•			10	—	—	.15V/mW	Room	1	10	—	CF
Raytheon Co.	InSb	•			2-5.5	1.5×10^{11}	—	3.6A/W	77K	—	1×10^{-3} -10	Vacuum dewar	CF
	HgCdTe	•			8-12	4.5×10^{10}	—	$1.5 \times 10^4 \text{ V/W}$ (11 μm)	80-100K	500	2.5×10^{-3}	Multi-pin vacuum & non-vac.	CF
Sanders Assoc.	PbSe	•			1-6	2×10^{10}	—	—	—	20-500	—	CF	CF
	PbS	•				2×10^{11}	—	—	—	—	—	—	—
Santa Barbara Research Ctr.	HgCdTe	•			8-12	$> 2 \times 10^{10}$	—	$> 4\text{A/W}$	77K Liquid nitrogen, cryostat	< 100	.1, .25, .5, 1.0	Stainless steel/glass dewar	—
	PbSe	•			1-6.5	$\geq 1.5 \times 10^{10}$	—	.01-.05A/W	295K, 193K, 77K TE cooled Liquid nitrogen, cryostat	≤ 50	.5 x .5, 1.0 x 1.0, 2.0 x 2.0, 3.0 x 3.0, 4.0 x 4.0, 5.0 x 5.0, 10 x 10	Stainless steel/glass dewar	—
	HgCdTe	•			8-12	$\geq 3 \times 10^{10}$	—	3-30A/W	295K, 77K Liquid nitrogen, cryostat	≤ 1	.25 x .25, .5 x .5, 1.0 x 1.0, 2.0 x 2.0	Stainless steel/glass dewar	—
	HgCdTe	•			10-20	$\geq 3 \times 10^9$	—	2-20A/W	77K Liquid nitrogen, cryostat	.1-.5	.25 x .25, .5 x .5, 1.0 x 1.0, 2.0 x 2.0	Stainless steel/glass dewar	—
	InSb	•			1-5	$\geq 8 \times 10^{10}$	—	1.6A/W	77K Liquid nitrogen, cryostat	< 1	.25, .50, 1.0, 2.0	Stainless steel/glass dewar	—
	HgCdTe	•			1-5	$\geq 5 \times 10^{10}$	—	5-50A/W	193K, 77K TE cooled	1-10	.25 x .25, .5 x .5, 1.0 x 1.0, 2.0 x 2.0	Stainless steel/glass dewar	—

CF = consult factory

COMPANY	MATERIAL	PC	PV	OTHER	SPECTRAL RANGE (μm)	D* ($\text{cmHz}^{1/2}/\text{W}$)	NEP ($\text{WHz}^{-1/2}$)	RESPONSIVITY (A/W OR V/W AT λ) (ROOM = 22°C)	OPERATING TEMPERATURE/ COOLING METHOD	RISE TIME (nsec)	ACTIVE AREA (mm^2)	PACKAGE TYPES	PRICE
Santa Barbara (cont.)	PbS	●			1-3.6	$\geq 4 \times 10^{11}$	—	.5-4A/W	295K, 193K, 77K TE cooled, Liquid nitrogen, cryostat	2-4	.5x.5, 1.0x1.0, 2.0x2.0, 3.0x3.0, 4.0x4.0, 5.0x5.0, 10x10	Stainless steel/glass dewar	—
	Ge	●			1-40	$\geq 1 \times 10^{10}$	—	1A/W	4.2K Liquid helium	<100 or <1	.5, 1.0, 2.0, 3.0, 5.0	Stainless steel/ dewar	—
	Si	●			1-30	$\geq 2 \times 10^{10}$	—	1.5A/W	4.2K Liquid helium	<100	.5, 1.0, 2.0, 3.0, 5.0	Stainless steel/ dewar	—
Silonex	Si				.4-1.06	—	1×10^{-13}	.65A/W (900nm)	-40°C-80°C	3	.8	TO18	CF
Thorn EMI	Si	●	●		200-1000	—	3×10^{-13} , 4×10^{-14}	20A/W	-70°C - +145°C	—	.05-12	TO5, TO18, TO52	—

Thermal Detectors

COMPANY	TYPE	SPECTRAL RANGE (μm)	RESPONSIVITY (A/W OR V/W AT λ)	RISE TIME (nsec)	ACTIVE AREA (mm^2)	PACKAGE TYPES	PRICE
Amperex	Pyroelectric	6-14 6-14	95-150V.W ⁻¹	—	2.1x0.9	TO5	\$5-\$9
Barnes Engineering	Pyroelectric	1-100	2400V/W/15Hz 400V/W/90Hz	≥ 150	1x2	TO5 T x R leader	\$605-3660
	Thermopile	.6-55	15V/W	80ms	1x1	TO5	\$99-300
	Bolometer	1-18mm	100-1000V/W	1.5ms	2.5×10^{-4} to 2.5×10^{-1}	Immersed in germanium lenses	\$2395
	Bolometer	.6-55	100-100V/W	1.5ms	.01-6	Flanged optical housing	\$635-735
Cooper Lasersonics	Pyroelectric	.001-1000	10^2 - 10^4 V/W/ (10.6 μm)	.5	1-40	TO5, TO8	\$100-550
Dexter Research	Thermopile	.1-50	25A/W-5V/W	30ms	.25-4.0	TO5, TO8	CF
EEV	Vidicon	8-14	>4A/W	—	18mm x 24mm	1" glass tube	CF
Eltec Instruments	Pyroelectric	1.5-1000	2700V/W (8-14 μm)	—	1.0x2.5	TO5	\$23.18
	Pyroelectric	.0001-1000	13 $\mu\text{V}/\text{W}$ (10.6 μm)	2	2.5x2.5	TO5	\$44
	Pyroelectric	1.5-100	5000V/W (8-14 μm)	—	1.0x2.5	TO5	\$30.38
	Pyroelectric	1.5-1000	45,000V/W (8-14 μm)	—	2.0	TO5	\$88
	Pyroelectric	1.5-1000	2000V/W (8-14 μm)	—	1.0x2.5	TO5	\$23.93
	Pyroelectric	1.5-1000	3600V/W (8-14 μm)	—	2.0	TO5	\$21.82
	Pyroelectric	—	48V/W (8-14 μm)	—	2.0	TO99	\$269.50
Eppley Laboratory	Thermopile	1-40	.1V/M	1	100	Varies	\$375-1500
Galai Laboratories	Pyroelectric	—	3×10^5 V/W	100	.05x.05- 3x3	—	\$1000+
Horiba Instruments	Thermopile	7-12mm	1550	.23	3.4	Single & dual elements, PZT ceramic on vibration mount	\$6-20

CF = consult factory

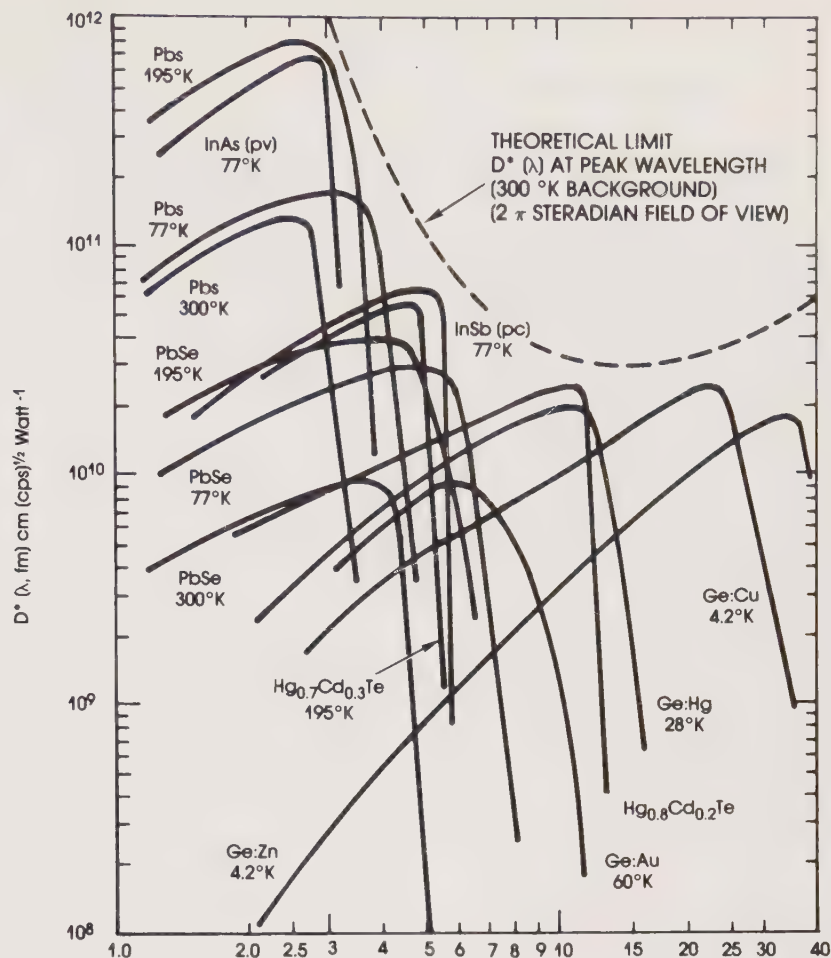
COMPANY	TYPE	SPECTRAL RANGE (μm)	RESPONSIVITY (A/W OR V/W AT λ)	RISE TIME (nsec)	ACTIVE AREA (mm^2)	PACKAGE TYPES	PRICE
Infrared Assoc.	(DTGS)	2-100	—	—	1×1, 1.3×1.3, 2×2	—	CF
Infrared Labs.	Ge Bolom.	2-5000	$>10^5\text{V/W}$	1000	1.0-8.0	Custom	\$3025
	Ge Bolom.	2-3000	$>10^5\text{V/W}$	1000	.20-4.0	Custom	\$2750
ISI Group	Zinc Selenide	.7-32	4.2 $\mu\text{A/W}$	—	—	—	\$9000-13,000
	Germanium	8-14	6.0 $\mu\text{A/W}$	—	254	—	\$9000-13,000
Laser Precision	Pyroelectric	.2-30	1 $\mu\text{A/W}$	—	1-12	TO5	\$275-675
LaserSonics	Pyroelectric	.001-1000	$10^2 \times 10^4$ (10.6)	.5	1-40	TO5, TO8	\$100-500
New England Rsch.	Lithium Tantalum	1-25	1 $\mu\text{A/W}$	—	1×1mm, 2×2mm	TO5	CF
Optomec Design	Liquid crystal paper	.8-20	—	—	5000	—	125
Oriel Corp.	Pyroelectric	.2-40	900V/W (15)	—	.1	—	CF
PlessCor Optonics	Pyroelectric	.1-35	—	—	2	TO5	CF
Pulse Systems	Pyroelectric	7-1000	5A/W	.07 .14	1×1	—	CF
QMC Instruments	Bolometer	100-10,000	5V/W (1100 μm)	1000	25	Dewar pre-amp	\$2500
Sciencetech	Thermopile	.25-35	100mV/W	10^{10}	506.7	—	\$475
Servo Corp.	Thermistor Bolometer	1-40	500V/W	1.0-4.0	.05×.05-2.5×2.5	—	\$1000-5000
Spiricon	Pyroelectric	.01-1000	—	—	.1×.1-.8×.8	—	\$980-27,500

Photoemissive Detectors

COMPANY	SPECTRAL RESPONSE RANGE (μm)	RISE TIME (nsec)	RESPONSIVITY (A/W OR V/W AT λ)	PRICE	COMMENTS
Instruments Technology Ltd.	.6-1.1	.1	.3mA/W (1.06)	CF	
NEC Electronics	.4-1.0	1.0	.45A/W (.85)	CF	
	1000-1600	.2	.77A/W (1.3)	CF	
	.6-1.1	1.0-10.0	.47 (.85)	CF	
	1100-1600	1.5	.78A/W (1.3)	CF	
Oriel Corp.	.2-1.1	2.2	2500A/W (400nm)	CF	Photomultiplier
PlessCor Optonics	1.3-1.6	1.0	.35A/W-.45A/W	\$1200/ea.	
Thorn EMI Electron Tubes Ltd.	.165-1.1	10-15	1mA (1000nm)	CF	
TRW Inc. Optoelectronic	.4-1.2	50.	.58A/W	\$470 Qty. 1000	

CF = consult factory

Detectivities and Characteristics of Some of the Most Commonly Used Infrared Detectors



Courtesy: T. Limperis, Willow Run Laboratories,
 University of Michigan and Honeywell EOO

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MATERIALS PROCESSING SYMPOSIUM

Chairman — Conrad Banas and Gary Whitney
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A principal objective of the 1986 Materials Processing Symposium will be to address the need for a more convenient information base in this field. Therefore topics of interest will include identification of the state-of-the-art, reviews of production experience, procedures for establishing process and equipment specifications, and guidelines for more uniform representations of performance information. The symposium will address advanced processing concepts as well as fundamental studies in all areas of laser materials processing.

MEDICINE AND BIOLOGY SYMPOSIUM

Chairman — Ronald Kirschner
Institute of Applied Laser Surgery
Michael Unger
Pennsylvania Medical Center

The Medicine and Biology Symposium will stress new applications, new instrumentation, and new accessories for laser systems used in medicine and surgery. Included will be presentations on new developments in laryngeal, intra-nasal, and endo-bronchial surgery. The meeting will also highlight pioneering efforts in laser surgery and feature a review of the changing laser frontier by two of these pioneers.

OPTICAL INFORMATION PROCESSING & DISPLAY

Chairman — John Caulfield
Center for Applied Optics
University of Alabama in Huntsville

Optical information processing offers unique potential in terms of high speed, 3-D interconnections, and truly massive parallelism. Perhaps only optical computers will be fast enough to drive 3-D graphic displays. This symposium will be devoted to new developments in the processing and the display of information using optical methods.

OPTICAL TECHNIQUES FOR INDUSTRIAL MEASUREMENT AND CONTROL

Chairman — Murray Penny
General Electric
Research and Development Laboratory

The use of lasers and electro-optics for scientific measurements has expanded rapidly over the last decade. Now we are seeing the same explosive growth in industrial measurement technology, driven by the maturation of optical techniques and the need for increased automation. Examples include techniques for measuring motion, clearances, surface finish, chemical composition, temperature, weld quality, subsurface structure, strain, and part dimensions in 3-D. This symposium will cover advances in optical measurement and control devices as well as the application of such devices in the industrial environment.

FLOW AND PARTICLE DIAGNOSTICS

Chairman — Dan Hirtleman
Arizona State University
Doyle Thompson
Purdue University

This symposium will cover instrumentation and measurement techniques for determining such parameters as mean velocity, turbulence, correlation functions, particle size and number density, species concentration, and temperature in fluid systems. Papers describing new solutions to difficult problems of optical access or measurements in harsh environments are encouraged. New developments in signal processing and data interpretation are also of interest.



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Laser Optical Parameter Measurement

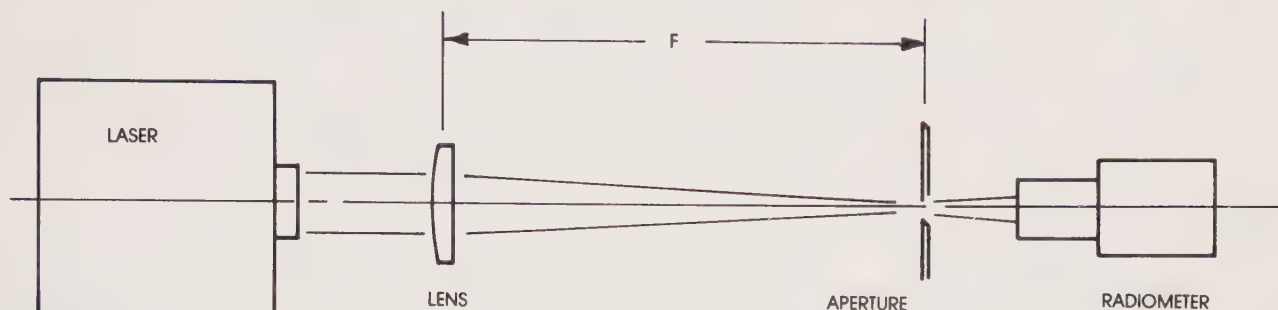


Figure 1.
Simplest divergence test setup.

There are many laser parameters — a huge number — that may usefully be measured. This article will not concern itself with anything electrical (such as prime power needs), acoustical or thermodynamic (such as coolant flow) so that it may more completely address the optical and optomechanical areas. All of these involve the laser beam itself and include:

- Radiated power (average and peak);
- Energy per pulse;
- Pulse width and shape;
- Pulse rate;
- Near-field profile;
- Far-field profile and divergence;
- Boresight;
- Focus (of passive elements such as receivers);
- Aberrations; and
- Spectrum.

One valuable aspect of many measurement techniques is that, if the equipment is designed properly, the techniques may also be used as adjustment and alignment tools.

What tools are available?

Amazingly few tools for measurement exist, really, especially if one is restricted to "off-the-shelf" equipment. Radiometers and other available detectors are usually neither designed nor coated for the proper spectrum. Furthermore, narcissistic reflections from test lenses can easily damage the laser itself. Telescope-type mirrors are available, but they generally have easily damaged coatings and focal lengths that are too short to be very useful. Silicon vidicon-type infrared TV cam-

eras have lenses corrected for the wrong spectrum and, worse, display strange patterns when used with monochromatic radiation.

Radiometers damage easily, and often have a nonlinear response to pulsed radiation. Many are also sensitive to positioning with respect to the laser beam. Detectors often have rise times comparable to the width of the pulse being examined, and sensitivity can be a strong function of temperature. Attenuating filters are often of only modest optical quality, reflective types are damage-prone and dangerous, and thermal lensing can be a problem with the absorptive types.

If this all sounds discouraging, it is meant to. Careless technique can be worse than a waste of time: it can actually be dangerous to both equipment and personnel. Some measurements are barely possible even with the best equipment and technique, and NBS traceability can be difficult to obtain. The best measurements are made with carefully designed do-it-yourself setups using the simplest possible optics.

Far-field measurements

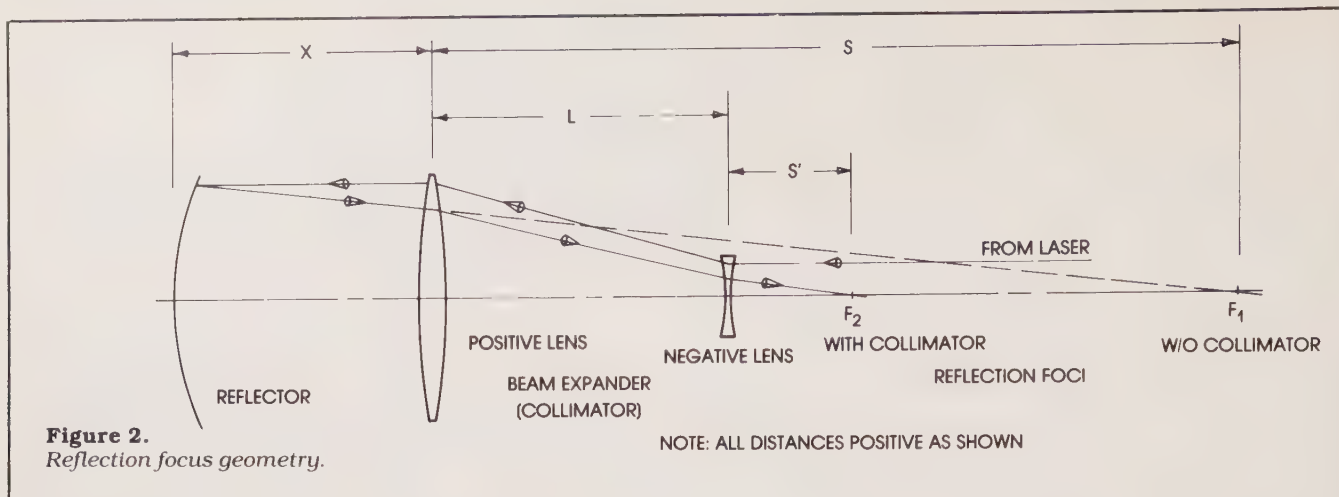
The two far-field parameters of general interest are divergence and profile. After defining divergence, we will start with a basic divergence measurement and then expand it to more accurate, higher energy and profile versions. I will use the pulsed Nd:YAG laser as an example.

The two ways of specifying divergence are in terms of integrated energy and energy density. Both require a lens (or mirror) to provide, at

its focal plane, an accessible map of the laser's far-field beam pattern. The integrated energy technique determines that aperture which, when carefully located on the focal spot, transmits a specified percentage (typically 80 or 90 percent) of the total laser output. The energy density technique determines, by some means that need not be calibrated, a peak energy density value (proportional to joules/steradian). It then picks some level below this peak, such as -10dB, at which the beam will be measured. The maximum spot width at this level is called the divergence. This second technique has many disadvantages and no apparent reason for being selected over the first approach, and therefore it will not be discussed further.

The most basic setup for measuring beam divergence is in Figure 1. A simple lens is placed in front of the laser and a removable, variable aperture is placed at the lens focus. The lens focal length is chosen to permit "reasonable" aperture sizes: 2–5mm is about right. So, a 1-meter lens works well with 1–5mrad "raw" beams, and a 10-meter lens is needed for the 0.25mrad or less that is typical of systems using beam expanders.

Unfortunately, all three pieces of test equipment in Figure 1 are capable of damaging the laser. Both surfaces of the lens, the front of the aperture plate (especially during adjustment, when the beam is not passing through the hole), and the radiometer input window all will reflect some laser energy back into the las-



er. Divergent reflections, such as from the curved lens surface, are no problem. The reflection from the plane surface of a 1-meter plano-convex lens, however, focuses only 50cm left of the lens — just about the space one would normally leave between lens and laser. This will put a dimple in any output window. Reflections from the radiometer window will converge more slowly after passing back through the lens, but they are convergent and, if aimed “right,” will focus somewhere inside the laser. The same is true of reflections off the aperture plate if especially, during setup, it is placed to the right of the lens focus. To understand this situation properly, we must examine the effect of beam expanders.

Beam expanders

Referring to Figure 2, we are given a beam expander of length L and magnification M . Something out front is producing a convergent reflection, which, left to its own devices, would focus at F_1 at a distance S from the collimator input. The action of the collimator lenses brings the focus in to F_2 , much closer to the negative lens. In fact, if the reflection is converging rapidly enough, it will focus in between the lenses. The formula for S' is

$$S' = S/M^2 - L/M.$$

First, notice well that, if $S = ML$, then $S' = 0$, which means the reflection is focused inside the negative lens. It follows that if $S < ML$, the focus is between the collimator lenses, and the above equation is no longer applicable.

For the common case of $S > ML$, the M^2 term does a very good job of keeping the focus in near the beam expander where it has the greatest potential for damage.

An example is probably in order.

With the Figure 1 setup, if $F = 10$ meters, the reflection from the plano lens surface will be 5 meters left of the lens. Now assume a $10\times$ beam expander 25cm long and 50cm ($= X$ in Figure 2) from the test lens. The formula gives $S' = (500 - 50)/100 - 25/10 = 2.0$ cm right of the negative lens, just about where the final folding mirror usually is located. A one-meter test lens would, in an otherwise identical setup, focus exactly on the positive lens of the beam expander. Reversing the 10m lens would move the focus in (depending on the glass used) to approximately 170cm. In this case $S = 170 - 50 = 120$ cm and $ML = (10)(25) = 250$ cm so the focus will be between lenses. This is a good place to have it unless there is a folding mirror in the middle of the collimator.

More on far-field measurements

From the above analyses, it would appear that a long-focus (ca. 10 meters) plano-convex lens should be used with its flat surface toward the laser, assuming analysis indicates that nothing will be damaged. For a similar short-focus (ca. 1 meter) lens in the same orientation, the reflection focus is only 17cm to the left of the lens. A spacing of 30cm or so between lens and laser should therefore avoid all problems. In both cases, the lens should be tilted about $1/2^\circ$ to avoid problems from the flat lens surface.

If energy densities are low enough (e.g., less than 50 mJ/cm² for a 20nsec pulse at 1064nm), the lens in setup 1 might be replaced by an aluminized mirror. Since operation is now necessarily off-axis, the aberrations must be carefully examined to insure accurate results; the formulas in Smith¹ are very handy in this regard. The result might be a setup like that shown in Figure 3.

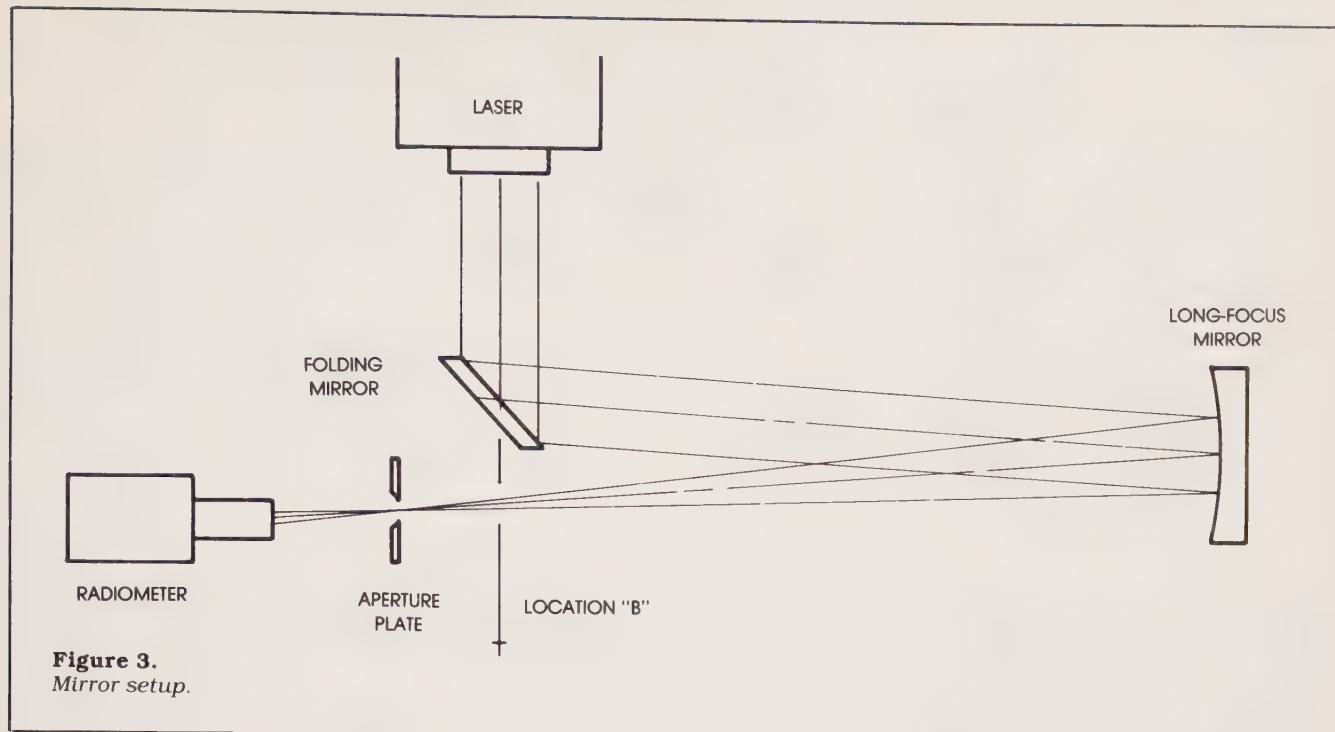
One advantage of a mirror is that, unlike the lens, its focal point can be accurately located via visual autocollimation, thus increasing the probability of accurate data. The lens is now completely eliminated as a source of narcissus problems; this is one of the biggest reasons for using a mirror instead of a lens.

Improved accuracy

The above techniques require a stable laser output, at least on the average, in order that the aperture “in” and “out” readings can be compared. The use of a second radiometer would permit single pulse measurements, with a corresponding significant increase in accuracy. To do this, simply make the folding mirror in Figure 3 partially transparent, and place a radiometer at location “B.” A run with no aperture will correlate the two radiometers, after which the use of several calibrated apertures will provide a crude profile, called a “Radial Energy Distribution,” from which divergence is obtained graphically. The transmission of the folding mirror must, for best results, be insensitive to polarization, its second surface should be tilted and AR-coated, and the two radiometers should be identical electronically.

Higher energy

The laser energy will generally erode the aperture plate in the setup above. In fact, such setups are sometime focused acoustically. For high-power lasers, this effect obviates the possibility of accurate measurement, making some form of attenuation mandatory. The quickest way to do this is to remove the reflective coating from the mirror in Figure 3. The result will be about 14dB attenuation, which can be accurately calibrated if the mirror material is known. The back of the



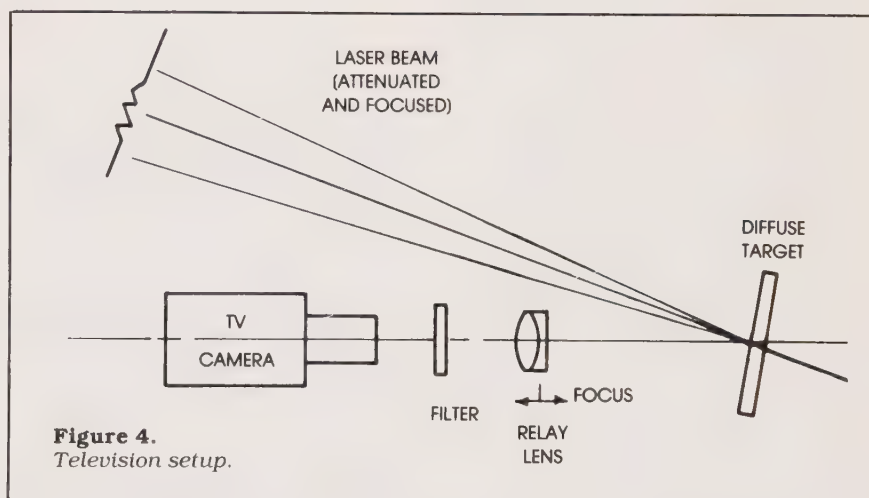
mirror should be ground to disperse the waste energy. Many other approaches based on dielectric reflection are also possible. Filters should be avoided.

A crude profile measurement has already been described. More detailed, albeit somewhat qualitative, data can be obtained via a TV camera. As shown in Figure 4, a diffuse target is placed at the focus of one of the previous setups, in place of the aperture plate. A relay lens is used to focus the TV on this target, and the laser is attenuated so that it will not damage the target. The geometry should be calculated so that the expected laser spot is about half the height of the TV screen.

The camera lens should, if possible, be set between $f/8$ and $f/16$ and neutral density (ND) filters used to set intensity. A video recorder can be used to document the data and a selection of ND filters can be used to "slice" the laser spot at a variety of power density levels. During the test, the TV camera can be moved back and forth slightly to average out the impact of the "woodgrain effect" common to silicon vidicons (if, indeed, such a tube is used).

Boresight

Whenever boresight is requested, one must ask two questions: (1) *of what*, and (2) *with respect to what?* Then one must be sure the answers are adequate. Suppose, for example, that the requirement is to boresight the laser beam with respect to the laser mounting pads. What part



of the laser beam? If the center, how does one define the center of a typical, rather bedraggled, laser spot? And if the plane of the mounting pads is not normal to the nominal laser beam, how is the other axis defined? Pins? Another part of the case? There can be practical questions, too, such as, if a receiver is involved, how does one access the field stop, especially if the optics are designed for 1064nm and access must be visual?

Once these questions are answered, the technique often is obvious. For example, a common beam center definition is "the center of the circle containing 80 percent of the laser output." One has no choice except to use a radiometer and aperture. With a receiver, one must somehow (from back or front) illuminate the field stop so it is visible. If

the pad plane is supposed to be normal to the beam, a reference plate is needed that makes contact with those pads and has some sort of reflective reference surface. A polished glass or metal plate, or a metal plate with a cleverly mounted (i.e., stable) mirror, are all viable candidates for this.

A helium-neon laser is a powerful tool if a receiver, TV set, visual sight, reticle, or some other secondary equipment must be aligned to the laser. Incandescent lights are also useful, especially for initial rough alignment. Finally, it is best to keep critical jigs, fixtures, and alignments to an absolute minimum and have the test equipment, as far as possible, self-aligning. One setup is shown in Figure 5 for a laser transmitter and receiver to be aligned normal to the mounting pad plane.

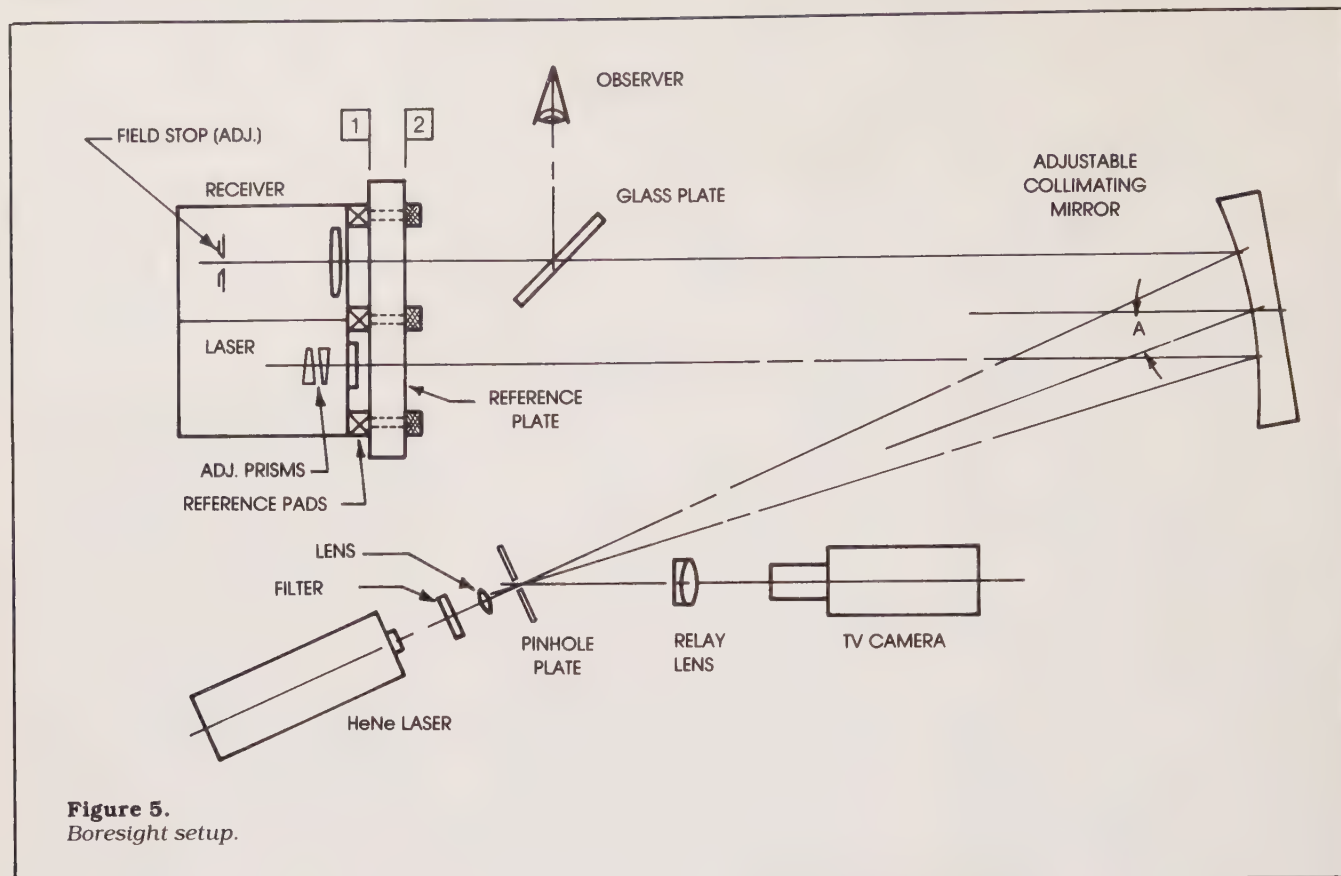


Figure 5.
Boresight setup.

An autocollimation technique is used for the measurement and alignment. Referring to Figure 5, a large glass (probably Pyrex) reference plate has three holes drilled in it for attachment to the laser mounting pads. This is the only sensitive part of the entire setup. The plate should be of high optical quality and have very parallel sides. Coatings are important: surface 2 should be antireflective (AR) for the laser and HeNe lines, while surface 1 should be AR for the laser and about 50 percent reflective at HeNe. This is because surface 1 is the real pad reference. The rest of the system is essentially as discussed previously, except for the HeNe laser. The filter in front of this laser protects it from the laser under test. The pinhole plate has a pattern printed on it to permit angular measurement. Angle "A" should be minimized to avoid aberrations.

The procedure is relatively simple. After setup, the HeNe lens is focused on the pinhole so the beam fills the collimating mirror. Then the collimating mirror-to-pinhole distance is adjusted until the reflection off the reference plate is focused on the pinhole plate, and then aimed at the pinhole. The relay lens is focused on the pinhole plate.

The HeNe beam will now be entering the receiver and, since it is slight-

ly defocused by the infrared optics, will appear as a red ring around the field stop. The entire laser is adjusted until this ring is centered on the stop, and the aiming error is measured at the pinhole plate. Next, the laser is fired, and its impact point (on the pinhole plate) observed with respect to the reference plate and receiver. If desired, both transmitter and receiver may be adjusted in this same setup.

The key to the entire setup is the fixture that supports the laser and reference plate. It must be designed very carefully to support the equipment without applying any stresses to the reference plate. Note that this assembly can even be put in a temperature chamber (with good windows) and tested dynamically over temperature, since the fixture is self-referencing.

Other measurements

Divergence and boresight are the two measurements that generally give the most trouble. Many of the others require only thermodynamic and electronic test equipment, with very little optical involvement. The spectrum of a production system rarely has to be checked. The same is true of the near-field profile, but all that is needed to examine this profile is a different relay lens with a TV camera.

Traditional aberrations do occur in lasers, especially spherical, but they are difficult to measure in a small-diameter beam. If the beam has been expanded to 5cm or more, a Hartmann test works very nicely with three-by-three or five-by-five plates with about 25 percent transmission. When combined with a (slightly defocused) far-field setup and TV camera, this can also become a powerful tool for collimator alignment.

Summary

The measurement of any laser parameter (except, possibly, size and weight) is a tricky business fraught with pitfalls. The boresight and divergence of a Q-switched laser are especially hard to measure correctly. Some practical, tested suggestions have been made, and the reader is encouraged to adapt these setups to his specific needs. One must be particularly careful in any such testing to protect both the test equipment and the laser being tested from any damage.

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Laser Optics: Design Considerations

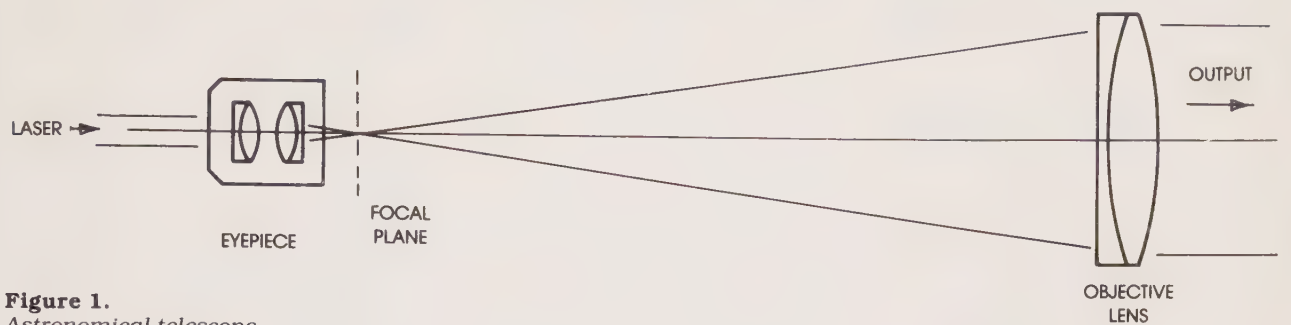


Figure 1.
Astronomical telescope.

The rapid increase in laser capabilities and applications has caused corresponding changes in associated fields such as electronics and optics. In particular, optical design takes on a whole new complexion where lasers are involved. Some work is much easier, while other tasks become virtually impossible, and some factors ignored previously have become critical. In this article, laser optics will be examined in the usual sequence, starting with generalities and working through simple systems to a look at the more complex applications.

Source characteristics

To begin with, it is useful to spend a minute or two looking at the unique characteristics of the laser as a radiation source. The one word "coherence" says almost everything and yet very little. The laser's most important optical characteristic is a very narrow spectral bandwidth; the "easy" monochromatic designs are often defeated, however, by either multiple wavelengths from the same laser or other functions (TV, visual sight, etc.) sharing the same optics.

All but diode lasers have relatively narrow beamwidths, or divergence (a few milliradians or so), and many are nearly diffraction-limited. Most have small output apertures (1–10mm diameter). Many are infrared; most important are those based on neodymium at 1.06 micrometer and the CO₂ gas lasers at 10.6 micrometers. Many are CW but these are often modulated. Others are pulsed, generally of either the long (milliseconds) or short (nanoseconds) variety. Pulse rates vary from single shots to several kilo-

hertz. The two lasers emphasized here are the common "HeNe" CW gas laser at 0.6328 micrometer and the pulsed Nd:YAG solid-state laser at 1.064 micrometer, the latter easily doubled to 0.532 micrometer.

Initial considerations

There are a number of considerations, both theoretical and practical, that are common to all laser optics. Most of these have to do with divergence angles. The diffraction limit, for example, is

$$\alpha = 2.44\lambda/d \text{ radians}$$

to the first dark ring of the "Airy disk," which contains at most 84 percent of the power from a "perfect" source. A laser "brightness" concept

$$B = \alpha D \geq 2.44\lambda$$

is convenient on some occasions; at 1.063 micrometer the best possible value for B is 2.6 mm-mrad. Typical brightnesses are within a factor of 10 of this value. An actual laser output consists of two components: correctable divergence, which is removable by an appropriate lens placed at the laser output; and uncorrectable, which is what remains after the best possible correction (some of which may be the removal of aberrations).

The term "near field" refers to the spatial distribution of energy density at the laser output. The "far field" is the angular distribution, which is roughly the same as the spatial pattern a long distance away.

There are several practical considerations. The optical media, for example, must *transmit* the laser

beam and not *absorb* it. Quick judgments are dangerous: the very clear 517642 (BK7) glass has a terrible time with 1.06-micrometer radiation. Coatings are much more critical than with camera optics. In the first place, laser energy is precious, and wasting it is unwise. Second, the energy so wasted can actually be injurious to both hardware and people. Finally, both glasses and coatings must be able to withstand the sometimes high laser power.

Adjustments must also be considered and included in the design. The laser output is invariably aligned to something else. This can be done mechanically or optically; if optically, elements can be tilted, translated, or rotated to accomplish the alignment. It is very easy to adjust unacceptable aberrations into a laser beam.

"Easy" optics

Using a 100 millijoule, Q-switched laser rangefinder as an example, problems will be examined both going out of the transmitter and coming back into a receiver. Going out, the "raw" laser beam is rarely narrow enough. Since brightness ($=D\alpha$) is more or less constant, divergence can be reduced by the simple expedient of an afocal lens system. You might first try an ordinary telescope, as shown in Figure 1, but this will fail for at least five reasons: (1) if the eyepiece has any cemented elements, they will be decemented by the laser; (2) the air at the intermediate focal plane will break down, attenuating and distorting the beam; (3) back reflections (narcissus) from poorly coated surfaces are almost sure to damage something; (4) the telescope objec-

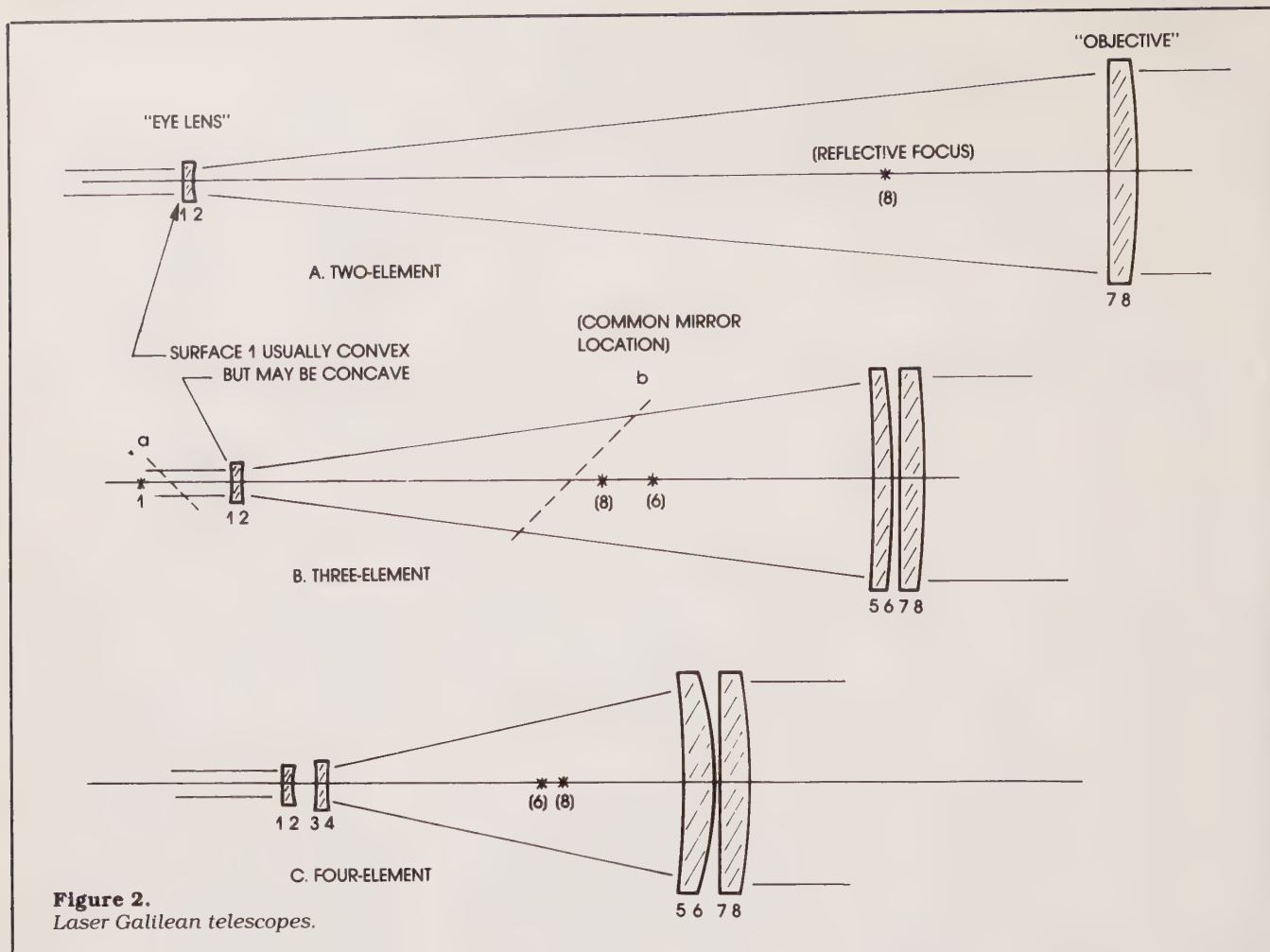


Figure 2.
Laser Galilean telescopes.

tive is probably too fast to be adequately corrected for a laser (the eye is very forgiving); and (5) if the laser is infrared, the spherochromatism of the lenses will be unacceptable.

Output collimators

The nice answer to this is a properly designed Galilean telescope, such as those shown in Figure 2. Only spherical aberration needs correction—coma must be watched but is, in this case, benign. The choice between the three versions in Figure 2 depends on the speed of the objective lens group. The simple form, Figure 2a, is more than adequate for designs slower than $f/5$. Add one element (Figure 2b) for speeds between $f/3$ and $f/5$. The four-element version is useful down to about $f/1.8$.

To design such collimators, first select the glasses to be used. The objective should have as high an index as possible: Schott's SF10 and SF14 are good choices. The negative lens should have a high damage threshold: fused silica and Schott LaK8 have both worked well. No surfaces can be normal to the laser beam: any reflected energy should spread

at least 3-4 times the laser divergence. Mirrors are often placed at locations "a" and "b" in Figure 2b; care should be taken that reflections from surfaces 1 and 8 (along with 6, and sometimes 3 and 5 in the other designs) do not focus on these mirrors. The actual narcissus foci are marked on the Figure 2 designs. A good rule-of-thumb is to keep the reflection footprint at least half the input beam diameter on or in any element. To this end, the index of the negative lens can be changed at will without serious impact on spherical aberration.

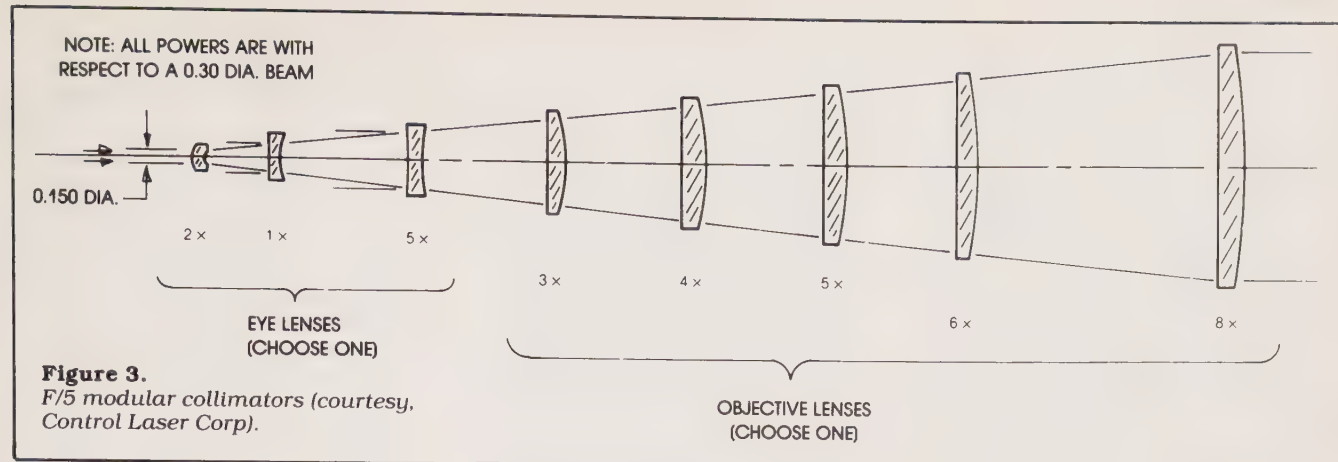
Galilean telescopes work nicely because the undercorrected objective spherical aberration is completely compensated by the overcorrection of the "eye lens." This means, among other things, that as magnification increases either the eye lens will bend to the right or the objective spherical will be reduced somehow. This can be done in designs B and C by bending the meniscus lens (5-6), and in design A by changing the objective glass.

Note that the output lens is plano-convex in all three configurations. There is no reason to deviate from

this, since the spherical residual in design B, for example, is at most 4 arc-seconds. This can often be reduced to well under one second by letting the output lens go biconvex, in what would appear to be a classic case of gilding the lily.

As long as lens speed and spherical aberration are held constant, it is easy to design a "modular" series of beam-expander lenses for a variety of input and output beams. Such a series, designed at $f/5$, is shown in Figure 3. This set provides for three input and five output beam sizes, with magnifications ranging from $1.5\times$ to $16\times$. All but the smallest of the objective lenses is plano-convex; the glass was varied to correct the spherical aberration, which has a residual of less than three arc-seconds for most of the combinations.

One final note: Coma for these collimators is always inward. Therefore, the comatic tail from off-axis rays tends to add to the center of the beam and improve divergence slightly over expectations. However, this also means that the input beam must be carefully aligned (sometimes within one milliradian) to the collimator axis. Looked at the



other way, lens tilt — especially the eye lens — is critical and must be either tightly toleranced or adjusted. Centration, on the other hand, can be sloppy without seriously aberrating the output beam. Decentration has, in fact, been used on some occasions as a beam steering technique.

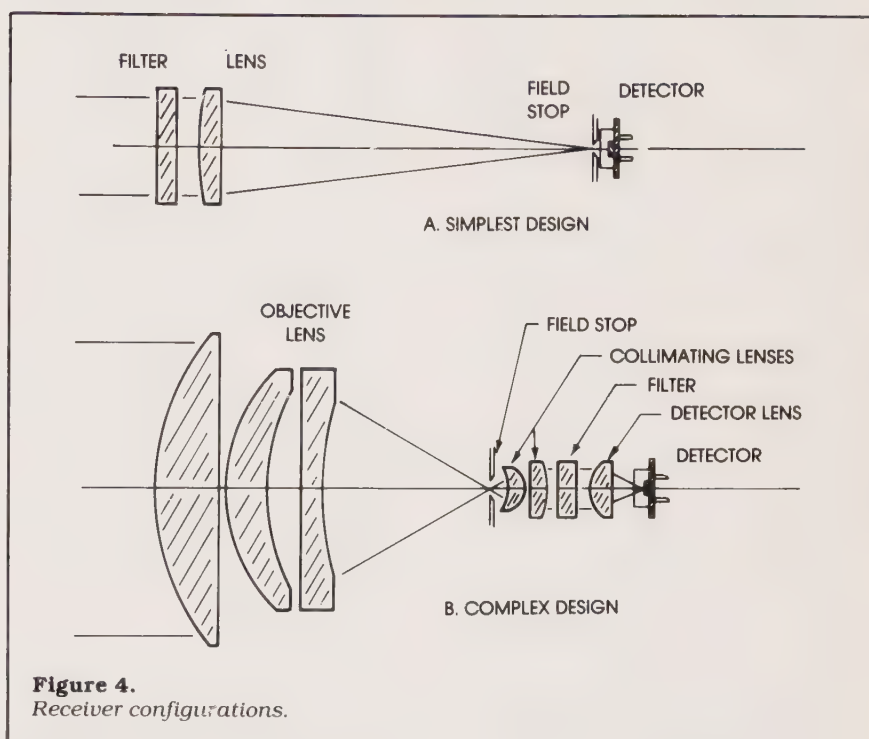
Receiver optics

Optics are needed to control receiver aperture, field of view and spectrum in laser rangefinders. The two design extremes are shown in Figure 4, and both will provide excellent performance. The simple version in Figure 4a employs a plano-convex lens of high index (to reduce spherical). The aperture of this design is limited by filter economics — diameters much over 3cm are possible but not usually rational for the narrow-bandpass (NBP) filters normally employed. Three centimeters is plenty, however, for a large number of applications. The field stop is cemented to the detector, giving it some added electromagnetic radiation protection. All the analysis needed centers around this stop: (1) it must be large enough to handle the laser (collimator) output divergency plus assembly tolerances (the latter generally dominate); (2) the lens spherical aberration should not be much greater than 20 percent of the stop diameter; (3) the detector must be large enough to handle the beam spreading behind the stop; and (4) coma must be considered if stop/detector translation is to be used for aiming purposes.

As an example, if the lens is SF10 glass, f/4 with $f = 10\text{cm}$, the spherical blur is:

$$B \approx 0.04/(f\#)^3 \text{ radian.}$$

which equals $625\mu\text{rad}$ or 0.06mm at the field stop. A typical field of view is 4mrad , for a 0.40mm stop diameter. Spherical is thus 15 percent of



the stop, which is acceptable. The stop-to-detector distance for one detector is about 3mm , giving 0.75mm spreading at $f/4$. The detector must therefore have an active area of at least $(0.75 \pm 0.40) = 1.15\text{mm}$ diameter.

Tighter field control or larger aperture requirements usually lead to a more complex design, such as that shown in Figure 4b. These optics can be divided into three very convenient groups: (1) the objective lens; (2) the field stop and collimating lens; and (3) the filter, detector lens, and detector. This last group can be sealed to provide superb stray light control.

Objective lens design only needs to consider packaging constraints, spherical aberration, and field of view (don't forget field stop adjustment for aiming). For coating economy, a single glass should be used.

Very compact lenses can be created — the design shown has two plano surfaces and a well-corrected speed $f/0.9$ — but such fast lenses pose severe mechanical tolerancing challenges.

NBP filters have a narrow acceptance angle at the laser wavelength. This varies with filter design, but 5° off-axis is a prudent limit if the filter characteristics are unknown. All rays should be kept within the filter limit. The detector and detector lens also have a finite field of view. For the design shown, the lens focal length is 10mm and the detector active diameter is 0.75mm , giving a 4-degree total field. This translates back to a very definite limit on field stop size, and in this case is much more restrictive than the filter itself. Incidentally, plano-convex singlets are usually adequate to the right of the field stop.

Adding other "colors"

There are two reasons for designing laser optics that function at more than one wavelength: function and test. The two primary examples are doubled YAG, for which the optics must handle both 0.532 and 1.064 micrometer and the use of HeNe lasers as alignment tools. Other examples, such as multicolor argon-ion lasers, abound. An example of each reason is shown in Figure 5. The receiver lens in Figure 5a is made parfocal for HeNe (0.6328 μ m) by the simple expedient of an air-spaced doublet. Note that it is much slower than the design in 4b. The wide wavelength spread leaves little room for finesse in glass choice; the computer will almost always raise indices and spread dispersions as far as it is permitted to go. As a result, almost any crown can be combined with any dense flint to produce acceptable results. Note that secondary color is not a problem when only two wavelengths are involved. This can be a trap, however, because the wide spread causes the focal length to change very rapidly with wavelength at the HeNe line. This in turn mandates tight tolerances to maintain a true parfocal condition.

The other example, Figure 5b, is a 5 $\times$ collimator for a doubled Nd:YAG laser. Note that only the objective lens is color-corrected. The eye lens can be a singlet as long as chromatic magnification variations of 2–5 percent can be tolerated. Note also that the objective has three elements. Zonal spherical for an air-spaced doublet, even as slow as $f/4.5$ (which usually is too slow to fit packaging constraints), can easily be over ten arc-seconds on a beam whose total divergence must

typically be less than 40 seconds. Spherochromatism is also often a problem, and both can be controlled with the third element in either a P-N-P arrangement or the N-P-P sequence shown. Two of the lenses can sometimes be cemented, for speeds slower than $f/4$ or so, but only when the energy density (1.064 micrometer, 20 nsec, 10 pps) is under 0.1 joule/cm² at the cemented interface. To design, first do the eye lens. Choose a high-index crown glass such as LaK8, make surface 1 slightly convex (one-meter radius is usually adequate), and select radius 2 for the desired lens speed. Then design the objective in the usual manner, minimizing the angles of 4 or 5 rays at each wavelength to simultaneously correct spherical, axial color, and spherochromatism.

Narcissus can be nasty with lenses. Reflection foci are generally strongly under-corrected, with minimum blur diameters of several millimeters, but in one case similar to that in the figure, the reflection from surface 6 was almost perfectly corrected. This, plus a marginal antireflection coating, caused air breakdown a few centimeters left of surface 3. While not in this case harmful to system performance, the snapping was distractingly noisy. Reflections from objective surfaces can easily focus in or to the left of the eye lens and must therefore be monitored carefully.

Other functions

The imagination is the only limit to both laser applications and the optics via which those applications are accomplished. Window area limitations, for example have caused some military systems to go to a

single objective lens through which a laser rangefinder (both transmitter and receiver), a television camera, a visual sight, and sometimes other functions all operate. Zoom lenses or power changers are often involved. Such designs are too complex to describe here but one suggestion is worth making: dichroic beamsplitters, always needed in such systems, should generally be designed to reflect narrowband light (i.e. laser) and transmit broadband light (TV, visual, etc.) at incidence angles of less than 45° — the smaller the better. The dichroic coatings designed this way will almost always be cheaper, more durable, and more efficient. Also pay particular attention to narcissus if, for example, an infrared TV is used with a Nd:YAG laser, since the bright laser can easily impair TV imagery.

Another kind of combined application occurs in laser machining, where microscope-type optics are employed that, again, often have to service a visual observer and a TV as well as the laser. One such design for a Nd:YAG laser, with an objective magnification of 3 $\times$ and a laser numerical aperture of 0.25, is shown in Figure 6. Conventional objective designs are generally not applicable for several reasons, including self-destructive narcissistic tendencies, cemented surfaces, and excessive spherical aberration at the laser wavelength. It is easiest to design these lenses for an infinity-corrected microscope because this puts the dichroic beamsplitter in collimated space and avoids many alignment problems. The design process will be an iterative sequence of visual design, narcissus removal, and laser adaptation.

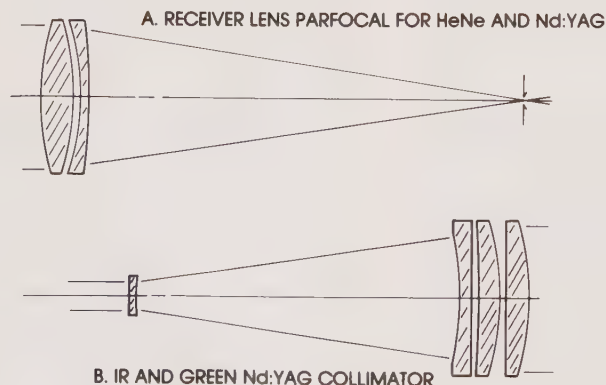


Figure 5.
Color-corrected laser lenses.

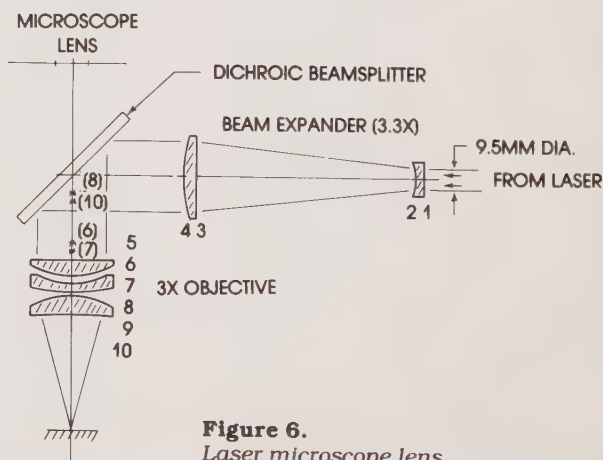


Figure 6.
Laser microscope lens
(courtesy, Control Laser Corp).

The visual design is rather traditional. Glasses are not critical, except that the crown and flint should have a large V-difference for narcissus reasons. The aperture stop, normally a 10mm hole just above the objective, shifts to the 20mm-diameter head lens. If its prescription can be obtained, this lens should be included in the design since it is not a traditional doublet. The field diameter is 7°. Performance should be very good, but need not be diffraction-limited.

Narcissus will force compromises in the design. Notice for example, how close the reflection from sur-

face 7 comes to surface 5. Originally it was inside the lens. Coma and lateral color were sacrificed to solve the problem; axial aberrations should be kept well-corrected. Glass thickness should be kept to a minimum, and air spaces will be found to be critical design parameters.

The laser collimator is then designed to solve the infrared focus shift and spherochromatism. The beam will be slightly convergent between collimator and microscope lens.

Conclusion

In short, laser optics are not hard

to design. In fact, in many ways, they are easy compared to many other applications, such as camera lenses. You must, however, pay attention to the special problems created by lasers, of which physical damage and human safety are the most important. Optical coating requirements are much more severe for lasers than for visual optics. Bulk transmission of glasses should not be taken for granted. And, finally, alignment and adjustment requirements are often important design parameters.

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Commercial Dye Laser Output Characteristics

Pump Source	Argon/Krypton Ion Laser	Nd:YAG Laser	Excimer Laser
Fundamental Tuning Range	380nm-950nm	410nm-880nm	320nm-970nm
Average Power	≤ 5 W 100 mW*	≤ 2 W	≤ 4 W
Repetition Rate (typ.)	CW ≈ 80Hz*	10-40Hz	25-500Hz
Peak Power	CW > 1kW*	≤ 20MW	≤ 10MW
Energy/Pulse (typ.)	CW 1nJ*	20-120mJ	40-120mJ
Pulsewidth	CW <10 ps*	5-10nsec	7-20nsec
Bandwidth	down to 500kHz	600MHz-6GHz	150MHz-6GHz

*mode-locked

Source: Lambda Physik

Laser Damage Testing

Laser-induced damage testing (LIDT), or the deliberate exposure of an optical component to intense laser radiation to determine its failure level, is not new. The proceedings of the annual Boulder Damage Symposium document 16 years of progress in resolving such fundamental issues as why and how laser-induced damage is initiated in different bulk materials and at bare and coated optical surfaces.¹

The driving force behind this effort has always been the same: the achievable output of high-power laser systems is limited ultimately by the durability of the components in the optical train. Fueled by the Strategic Defense Initiative and continuing interest in laser fusion, efforts to develop superior materials and coatings seem destined to accelerate. These programs and the supporting damage test facilities have been the nearly exclusive province of major government, university, and industrial R&D laboratories.

Tried-and-true designs

A recent and largely unheralded trend toward more routine uses of LIDT has emerged. The subjects here are the tried-and-true coating designs and materials widely used

for military *low-energy* pulsed laser system components. Today the independent damage test laboratory offers the optics buyer services that are useful in specification development, acceptance testing, and qualification of new suppliers for "approved vendor" status. Optical component suppliers in turn find LIDT useful for product improvement, process control and failure-cause diagnosis.

This trend is driven by the special importance of optics reliability in military systems. The laser sources used in rangefinders, designators, illuminators, search-and-track systems, etc., operate in the visible and near-IR spectral regions, and are characterized by pulses of relatively low energy ($\sim 100\text{mJ}$), short duration ($\sim 15\text{nsec}$) and moderate repetition frequency ($\sim 20\text{Hz}$).² They are precisely engineered devices that extract maximum performance with high efficiency from ruggedized packages of minimum weight and volume.³ They must be available on demand to meet mission requirements, which often include operating under adverse conditions for long periods of time without adjustment or maintenance. Since replacement of damaged optics is a costly

and time-consuming operation that cannot be performed in the field, the usual consequence of failures like these is an unacceptable system down-time.

Despite the best efforts of the system engineers and their suppliers, laser optics failures do occur. Almost always, the coated surfaces are the weak links.

Given all this, it is easy to appreciate the importance of routine LIDT to the military optics acquisition process; procurement specifications now often include damage testing as a requirement. In this article I will review applications of LIDT to the procurement and qualification of durable optics for low-energy pulsed laser systems, examine some critical issues that bear on the relevance of laboratory damage test results to the actual service conditions and provide a checklist of items to consider when preparing a damage test plan or procurement specification. To begin, it is helpful to review briefly the fundamentals involved in laser damage testing.⁴

A damage test primer

A typical calibrated laser damage test system is shown in block form in Fig. 1. Radiation obtained from a sta-

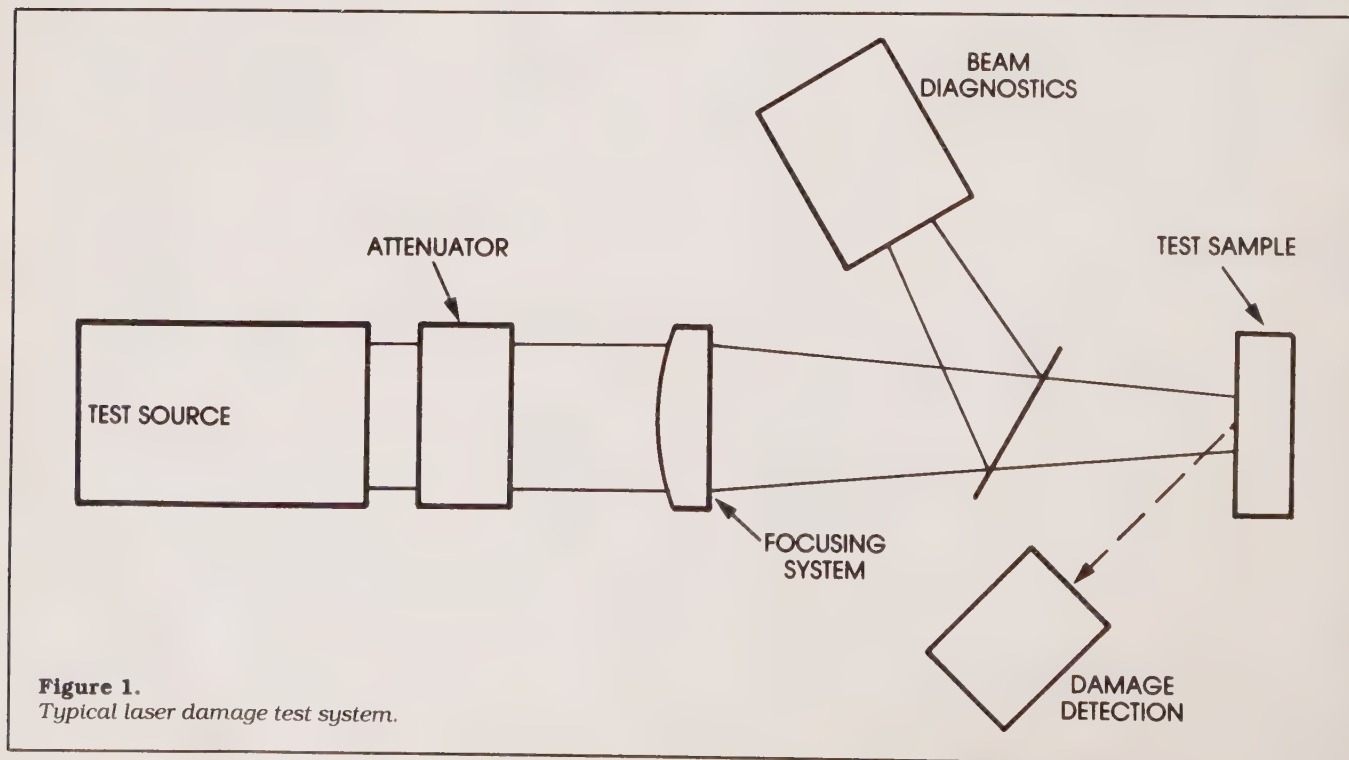


Figure 1.
Typical laser damage test system.

ble, well-characterized laser source is focused to destructive intensities at the sample with a high-quality optical system. Essential components include a beam attenuation system that permits changing the energy delivered to the sample without changing the operating parameters of the laser itself, and a beam-diagnostics package that, as a minimum, permits determining the total pulse energy and the distributions of energy in time (the temporal profile) and space (the spatial profile).

The spatial profile evolves as it propagates and must be determined in the target plane or equivalent. The sample to be tested is mounted in a precision manipulator so that different exposure sites can be indexed into the beam. An on-line damage detection monitor is used, and a differential interference contrast microscope (not shown here) provides for the off-line damage verification and analysis.

To be sure, an absolutely calibrated system provides maximum utility and experimental versatility, but requires exceptional care in laser source characterization to maintain consistent, accurate results. Historically, this approach has been followed by the laser materials R&D labs. But at least one major military laser systems manufacturer has had success at acceptance testing with a *relative* damage tester, which provides a back-to-back comparison between the test sample and a "reference" piece.

One good thing is that minimal diagnostics are required with this approach. The references are coatings that have always proven durable in service, so durability equivalent to a reference sample is considered acceptable. If the reference has been previously characterized in an absolute system, the relative damage tester becomes a *comparative* system. This approach forms the basis for the vendor qualification and acceptance test procedures in a comprehensive laser optics procurement specification now being developed by the United States Army Missile Command.⁵

Test according to needs

Different damage test procedures are employed depending on the results required. In a *certification* test, the sample is exposed at a single specified irradiation level and monitored for damage to verify durability. The *lifetime* test is an extended certification in which the test piece is exposed for the specified length of time or number of pulses. In a *thres-*

hold test, many sites are exposed to different intensities to determine the minimum necessary to induce damage. *Surface mapping* tests are employed to establish sample uniformity and to determine the density of incipient failure sites.⁶ *Specialized* tests meet unique requirements, e.g. evaluating the subthreshold power-handling capability of detectors and optical sensor systems.

Damage test results are reported in terms of maximum pulse intensities (W/cm^2) or fluences (J/cm^2). The parameter routinely measured in a damage test, however, is the pulse energy (J), since this may be done simply and accurately with a commercial calorimeter. The temporal and spatial profiles are analyzed only periodically. Rigorous relationships between pulse intensity, fluence, power, and energy follow from integration of pulse profiles (see "Laser Pulse Characterization" below).

TABLE 1.
DAMAGE TEST ISSUES.

- Is the damage definition meaningful?
- Is the test procedure appropriate?
- Are the samples representative?
- Do the test parameters represent hardware?
- Is the safety margin adequate?

Testing types

You can do damage testing for many reasons, but the types that are most useful in enhancing the quality of military optics include:

● **Acceptance testing:** Lot-sampling tests performed on delivered optics or witness samples enable optics buyers to identify and reject weak lots before installation in system hardware, reducing the likelihood of costly optics replacement. Threshold tests commonly are employed; often the simpler certification test is adequate.

● **Durability certification:** Armed with the results of certification tests, optics suppliers prepare quotations with confidence, and qualify for "approved vendor" status.

● **Product improvement:** Threshold and surface-mapping tests performed in conjunction with surface science studies (for example, SIMS, ESCA, etc.) as part of an iterative

LASER PULSE CHARACTERIZATION

In a target plane normal to the propagation axis, the instantaneous local intensity $I(x,y,t)$ can be described by a spatial profile function $g(x,y)$ and a temporal profile function $h(t)$:

$$I(x,y,t) = I_0 g(x,y) h(t).$$

I_0 represents the peak axial intensity (W/cm^2). Integration over the duration of the pulse yields the axial fluence F_0 (J/cm^2):

$$F_0 = \lim_{\substack{x \rightarrow 0 \\ y \rightarrow 0}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x,y,t) dt = I_0 \int_{-\infty}^{\infty} h(t) dt = I_0 T_{\text{eff}}.$$

The integrated temporal profile function has units of time and represents an effective pulse duration T_{eff} . Peak power P_0 (W) results from integration over the target plane:

$$P_0 = \lim_{t \rightarrow 0} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x,y,t) dx dy = I_0 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x,y) dx dy = I_0 A_{\text{eff}}.$$

The integrated spatial profile represents an effective cross-sectional area A_{eff} . Integrating intensity over both time and space yields the total energy (J):

$$E = I_0 A_{\text{eff}} T_{\text{eff}}.$$

product development program will lead to improved coatings and optical materials.

● **Process control:** Routine lot-sampling helps ensure batch-to-batch consistency. The occasional weak lot is identified and can be corrected before shipment of the product to the customer.

● **Failure diagnosis:** Specialized tests performed on prematurely failed optics can reveal useful information about failure cause, level, damage morphology and defect density. In conjunction with surface science, failures due to surface contamination, impurity content, or incorrect coating design frequently can be identified.

Critical issues in the test

A number of issues must be addressed when specifying or planning the damage test if the results are to be meaningful. Selection of an appropriate test type has been touched on above. Other issues are listed in Table 1. In each of these, it is necessary to distinguish between the system characteristics and test-sample properties.

The problem of appropriately defining "damage" provides a good illustration of this need. In V-type antireflection coatings on glass substrates, the first observable change is a very subtle, nonpropagating pitting that occurs well below catastrophic failure, and is detectable only at high magnification or as increased surface scatter.⁷ Whether this pitting represents a significant degradation depends on the application: It may cause unacceptable loss if it occurs within the laser resonator itself, or it may be of no consequence on an external window. If you do not know system tolerance to subtle degradation, then take a conservative approach that defines any observable change as damage.

With regard to the choice of test samples, it is seldom practical to verify the durability of each optic delivered, so a lot-sampling approach may be appropriate. Useful lot-sampling guidelines exist.⁸ Either witness pieces or actual coated optics intended for hardware may be used to test durability, but care must be taken to ensure that the test pieces truly represent the entire optics lot. If a witness is chosen, substrate material, surface finish, coating, and pretest cleaning procedures must be as specified for the actual optics. Simple geometries are adequate and often easier to test.

Durability may depend strongly upon test parameters such as wave-

length, spot size, pulse duration, repetition rate, modal content, polarization state and so forth. It is sound practice to select values that will represent the operating environment to the maximum extent possible. Where repetitively pulsed testing is appropriate, take care to avoid exposure schemes that precondition the test site, as contaminant desorption may dramatically increase apparent durability.⁹

Spot size and modal content

At least two system parameters are not easily simulated in calibrated test systems: spot size and modal content. To achieve damaging intensities, it usually is necessary to focus the radiation; thus the spot size at the test site is less than the operational beam cross section. It must be greater than the mean separation (typically 50-100 μ m) of the coating defects at which damage initiates.¹⁰ A spot size of $\sim$ 500 μ m is usually adequate.

The question of modal content is more difficult to treat. Calibrated damage systems employ single-mode sources with reproducible spatial profiles, while pulsed, low-energy military systems employ highly

multimode resonators. Mode competition leads to transient local intensity maxima ("hot spots") that appear randomly across the lasing aperture. As a result, single-mode damage thresholds may be more than an order of magnitude greater than multimode values estimated from pulse energy, pulse duration, and beam cross section.¹¹

This disparity illustrates the need for incorporation of an adequate safety margin in any durability specification. Little help has been available to the system engineer in this task. Derating criteria exist for the electronic components in military hardware, but not for the optics, even though optics failures often are the most costly and troublesome to correct.¹² Theoretical guidelines for estimating upper bounds on local intensity maxima do exist, however, and recent advances in beam profiling systems and software may permit direct experimental evaluation of spatial profile variations, reducing the difficulty in relating single-mode damage measurements to multimode hardware.^{13, 14}

Once the critical issues have been decided, the detailed test specification follows. Table 2 contains a

TABLE 2. TEST SPECIFICATION CHECKLIST

Sample description:	
Drawing number	XXX-XXX
Substrate:	BK-7 glass
Size:	1" dia. $\times$ 0.125" thick
Coating:	40% R @ 1064nm
Preparation:	Methanol drag-wipe
Pre-exposure inspection:	Nomarski, 300x
Test Parameters:	
Test type:	Threshold
Wavelength (nm):	1064
No. of sites exposed:	25
No. of shots per site:	$\leq$ 100
Incidence angle (deg):	$\sim$ 1
Polarization:	Linear, S-plane
Repetition frequency (Hz):	10
Axial modes:	See note 1.
Pulse width (FWHM, nsec):	12
Transverse modes:	TEM ₀₀
Spot size (FW1/e ² , mm):	0.5
Special requirements:	None
Damage definition:	
On-line detection:	Surface alteration Enhanced scatter
Post-exposure inspection:	
Damage morphology:	Nomarski, 300x See note 2.
Test result:	See note 3.

Notes: 1. Multiple axial modes; "smooth pulse" option. 2. Threshold damage morphology is surface pitting. 3. Threshold range, 850-1020 MW/cm².

checklist of experimental parameters that may be used in its development. The checklist serves equally well as a vehicle for reporting test results. The example parameters, which were used recently in a comparison of output couplers from several suppliers, provide a reasonable starting point for meaningful testing of other optics types as well.

Steven C. Seitel
Montana Laser Corp.

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Typical Range of Electro-Optical Power Supply Parameters Suitable for Switching Mode Power Supplies

Application	Most Common Input Voltage	Range of Output Voltage Required	Range of Starting Voltage Required	Range of Output Current Required	Range of Output Power Required	Type Regulation Required
LASER						
HeNe	12-24VDC 115-230VAC	0.5 to 6KV	8 to 18KV	3 to 12mA	3 to 12mA	Current
HeCd	115-230VAC	2 to 5KV	12 to 18KV	25 to 200mA	50 to 250W	Current
CO ₂	28VDC	1 to 16KV	5 to 20KV	2mA to >200mA	2W to 2KW	Current
Semiconductor Laser	6 to 28VDC 115-230AC	2 to 400V pulsed		0-100A pulsed	0 to ≥12KW pulsed	Pulse Current
CAP CHG Flashlamp	12-24DC 115-230VAC	0.3 to >5KV	HV Pulse		1W to 2KW	Constant Power, Constant Current, or Constant Voltage
N ₂ O Laser	28VDC 115-230VAC	20-30KV			10W to 2KW	Constant Power, Constant Current, or Constant Voltage
Flashlamp Simmer	28VDC 115-230VAC	20 to 400V	HV Pulse	10 to 200mA	10 to 100W	Current
DETECTOR						
PMT	0 to 28VDC	0 to 3KV		0 to 3mA	≤5W	Voltage
APD	0 to 28VDC	100 to 500		≤1mA	≤1W	Voltage
PIN	0 to 28VDC	20 to 150		≤1mA	≤1W	Voltage
IR IMAGE CONV.	1 to 12VDC	8-16KV		≤1mA	milliwatt	Voltage

Source: Power Technology, Little Rock, Ark.

Typical Scanner Performance Comparison Chart

	Reflective Scanners			Diffractive Scanners	
	Resonant Galvanometer	Var. Freq. Galvanometer	Rotating Polygon	Acousto-Optic Deflector	Rotating Hologram
Aperture, mm	10	10	20	6	6
Scan Angle, deg.	30	30	40	3	40
Resolvable Spots/Scan (Rayleigh)	8200	8200	22,000	500	6600
Scan Rate, Hz	4000	300	7200	10,000	2400
Scan Throughput, megapixels/sec	32.8	2.5	158	5.0	15.8
Random Access Time, msec	N/A	1.5	N/A	0.01	N/A
Incoherent Light Compatibility	yes	yes	yes	no	no
Cost, with Electronics	\$400	\$500	\$15,000	\$3000	\$3000

A wavelength of 632.8nm has been assumed where necessary.

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Laser Safety Regulations

The US laser industry is now operating under sweeping new federal safety regulations that, for the first time in nearly a decade, radically alter the way lasers are built and used.

There are several new requirements that are more stringent than the old ones, and these will take effect in one year. And there are some new standards that may be more confusing than the ones they replaced. We'll get to the few negative points later. But first, a quick review.

It all started with the Radiation Control for Health and Safety Act of 1968, which made the Food and Drug Administration the national nanny for products that emit radiation. Lasers — for most people, at least — are neither food nor drugs, but FDA's in charge of them anyway. So along with microwave ovens, medical devices and tanning booths, the FDA must make sure that laser products won't harm the public.

Doing what's needed

FDA issued the first set of laser safety rules in 1976, and four years later announced it wasn't entirely happy with them. For the last five years it's been trying to decide how to modify the 1976 rules. Those modifications were unveiled in their final form last summer. See the August 20, 1985, *Federal Register* (Vol. 50, No. 161, p. 33682) for the 20 pages of fine print explaining them.

Just what do these new rules do? In a word, plenty. They cover everything from defining what a "safe" laser is to whether safety labels should say "Danger" or "Caution."

"Overall, it's a definite improvement over what the FDA had before. I think they went a long way towards doing what needs to be done," said laser safety consultant Bob Weiner, head of Weiner Associates. R. James Rockwell, a laser safety advisor operating out of Cincinnati, Ohio, agrees: "There's no question that the impact is a basic relaxation in most areas. It puts low-power lasers, in particular, in a much more relaxed condition."

In fact, the FDA in one fell swoop erased a long list of standards that basically required laser manufacturers to treat a five-milliwatt HeNe laser as if it were a five-watt argon la-

SUMMARY OF BASIC LASER BIOLOGICAL EFFECTS		
Photobiological Spectral Domain	Eye	Skin
Ultraviolet C (200nm-280nm)	Photokeratitis (damage to outer epidermal cell layer of cornea)	Erythema (sunburn) Skin cancer Accelerated skin aging
Ultraviolet B (280nm-315nm)		Increased pigmentation
Ultraviolet A (315nm-400nm)	Photochemical cataract	Pigment darkening
Visible (400nm-780nm)	Photochemical & thermal retinal injury	Photosensitive reactions
Infrared A (780nm-1400nm)	Cataract, retinal burn	Skin burn
Infrared B (1.4μm-3.0μm)	Corneal burn, aqueous flare, cataract?	
Infrared C (3.0μm-1000μm)	Corneal burn only	

ser. The agency, or more precisely FDA's Center for Devices and Radiological Health (CDRH), did it by simply lumping lasers in the 1mW to 5mW range into a new safety class (Class IIIa), and then declaring this new class to be exempt from many previous requirements.

The reason for the change is quite simple: these commonly used lasers aren't nearly as dangerous as their more powerful cousins. As Rockwell said, "They've put the hazardous lasers in the 'box' where they belong...[the Class IIIa lasers] are a modest hazard and require only modest controls."

Here's a brief rundown of the changes in CDRH's hardware requirements for lasers emitting 5mW or less in the visible range:

- Key-controlled master switches are no longer required;
- Remote interlock connectors have been eliminated;
- Multiple interlocks for preventing access to laser light during service and maintenance are no longer needed — simple switch-type interlocks will suffice; and
- The laser can output light as soon as it's turned on, instead of being delayed 3-4 seconds.

The new rules basically mean

these Class IIIa lasers need only have an indicator light to tell the user the laser is on, a beam shutter that can attenuate the light, and various CDRH-specified warning labels.

Perhaps the greatest relief to manufacturers is the dropping of the multiple interlock requirement, which meant they had to install complicated "fail-safe" interlocks on housings designed to be opened for servicing. Multiple interlocks are still required for lasers above 5mW, and even for the Class IIIa lasers if users or maintenance personnel could be directly exposed to laser light through the service opening.

"Human access" redefined

Outside of the changes in the bells and whistles, there's even more cause for optimism, as federal officials have changed the way they evaluate the effectiveness of laser housings. In regulatory jargon, this is known as limiting "human access" to laser light.

Under the old rules, a housing was deemed unsafe if a probe of infinite thinness could penetrate the exterior of the housing and, travelling in a straight line of no more than 1 meter, contact laser light. It wasn't important whether this light was ac-

LASER REGULATIONS AT A GLANCE

CHANGES EFFECTIVE SEPT. 1985

NEW CLASS IIIa — HARDWARE CHANGES

For most lasers in the 1mW-5mW range, the following hardware changes are made.

- Only simple switch-type safety interlocks are required on housings
- A master key-control lock is no longer required
- Remote interlock connectors are not needed
- Emission-delay devices do not have to be used
- Power switch may be substituted for beam attenuator if manufacturer justifies it to CDRH for a particular product.

NEW DEFINITION OF HUMAN ACCESS

- For the new Class IIIa, access will be determined by whether a part of the human body can physically contact laser light escaping from the product's housing
- For more powerful lasers, access is judged to occur if an "introduced flat surface" within the product housing can reflect light levels exceeding Class I out of the product. CDRH does not specifically define this flat surface, but offers the following guidelines:
 - The surface must reflect all of the laser beam

- Human exposure will be determined by the amount of this light that actually escapes from the housing
- Secondary reflections will not be used to make this determination
- Light escaping through transparent viewports is not to be considered when judging access
- Light reflected out of the housing will be measured with a 7mm measurement aperture, instead of the previous 80mm aperture.

MISCELLANEOUS CHANGES

- The words "laser light" can be substituted for "laser radiation" on warning labels for laser products in the visible range
- Certain medical lasers used for alignment purposes will not be required to carry the usual warning labels
- A special safety variance will not be required for demonstration Class IIIa laser products
- Dual-mode lasers in Class IIIb or above must incorporate scan-failure safeguards if a scan failure would cause light levels to increase from the Class IIIb level to the Class IV level.

CHANGES EFFECTIVE AUG. 1986

MORE RESTRICTIVE CHANGES

- OEM manufacturers will be required to provide CDRH, upon request, the names of customers who have purchased laser equipment
- A 50mm measurement aperture will be used to measure scanned laser light that may be viewed with optical instruments

- Manual reset mechanisms are required to take effect for Class IV lasers if there is an electrical power loss of more than 5 seconds or if the remote interlock connector is opened
- Emission indicators are required on control units if they are more than 2 meters distant from the laser or energy source
- The range of regulated radiation is expanded to cover wavelengths from 180nm to 1.0×10^6 nm (1 millimeter).

tually reflected out of the housing; mere contact with the beam was enough to make the product flunk the CDRH test.

That requirement has been dropped completely for low-power lasers, and substantially modified for high-power units. The new rules state that lasers of 5mW or less need only have housings tight enough so that no part of the human body — your finger, for instance — can be struck by laser light. That's all. No test probes, no unblocked 1-meter paths. If your finger can't be illuminated by stray laser light once the housing is slapped on the unit, the product will be in compliance with the new rules.

Things are not quite so simple for lasers above the 5mW cutoff point. While the infinitely thin test probe has been dropped as a test for these products, it's been replaced with a new "conceptual" standard. The concept goes like this: a product won't be considered in compliance if any light that's reflected off a "single introduced flat surface" in the interior of the unit can strike your finger (or any other part of the body) through an opening in the housing.

Representatives from the industry vehemently protested that standard when it was first offered in draft form, complaining that it was too vague to cope with. CDRH, for example, didn't specify the size of the "introduced flat surface," its reflectivity or how it should be positioned. The final rule published last summer still does not answer those questions, and for good reason. When judging compliance, CDRH will look only at how well a product's housing actually performs.

That may put more creative strain on designers, but at the same time it will give them more freedom to develop new housing designs. As Jerome Dennis, chief of CDRH's laser compliance unit, said, "the main thing that the standard requires is that the housing be effective." And CDRH did not leave manufacturers completely in the dark when it comes to evaluating safety compliance. They offered some common-sense guidelines for fooling around with this conceptual flat object.

For starters, the flat object must be large enough to intercept and reflect all of the laser beam. The reflected

light would then have to escape through some opening in the housing (such as a wire grid or a louver — windows and viewports don't count, and secondary reflections aren't important either) with sufficient intensity to violate Class I laser light levels (0.39μW).

The new standards, aside from allowing small gaps in the housings of low-power products, means that manufacturers can take a much more down-to-earth approach in making the more powerful lasers. "They're [CDRH] taking a big step toward making it much more realistic," said Weiner.

Aperture size altered

In addition to the new housing approach, CDRH has also adopted a less stringent method of measuring laser light. The new measurement standard, combined with the changes in housing regulations, should make the designer's job quite a bit easier.

In most cases, CDRH would allow the use of a 7mm aperture to measure the intensity of accessible laser light, instead of the old 80mm aper-

ture. This will be a big help to makers of products such as laser diodes, whose beams diffuse rapidly over a large area. In such cases, the 7mm aperture will record a much lower light level than the larger aperture.

And since "human access" is now measured at the point where light escapes from the housing (instead of where the probe intercepted the beam), the beam will have diffused even more. "By the time you get 20 centimeters away from a widely diverging beam," said Weiner, "you might have a Class I beam."

The agency will require a 50mm aperture, however, when measuring scanned or static laser light that's likely to be seen with "viewing optics" (otherwise known as cameras, binoculars, magnifiers, etc.). Surprisingly, CDRH used to employ only a 7mm stop when measuring scanned light that might be seen through viewing optics, so the new standard is tougher than the old one.

The new measurement standard won't affect most commonly used laser products, such as supermarket bar-code scanners or office equipment, but will affect laser light shows. Since the change is a more restrictive one, CDRH will delay its implementation until August 20, 1986.

And speaking of more restrictive changes, there are a few other hidden surprises in the new rules that manufacturers should take note of, namely:

- OEM laser component manufacturers will now have to register with

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CDRH, and provide a customer list to the agency upon request.

- A manual reset mechanism that forces the operator to manually turn the laser on after a power loss of five seconds, or after the remote interlock has been opened, will be required of all Class IV lasers (more than 500mW).

- Separate emission indicators are required for a laser system's operating controls if the controls can be located more than two meters away from the laser's head or its power supply.

- The light wavelengths regulated by CDRH have been widened to cover 180nm to 1.0×10^6 nm (1 millimeter).

The above changes won't take effect until August 20 of this year in order to give companies enough

time to phase in the changes. One change that will take effect immediately concerns the use of scanning safeguards, although CDRH says it's less a change than a clarification.

Companies loudly protested the draft language regarding scan failure safeguards, claiming CDRH wanted to have all high-power lasers automatically reduce their light level to 5mW or less in case of scan failure. But Dennis says the companies misinterpreted the complicated regulatory language in the draft proposal. He says the new proposal works as follows:

A Class IV laser product that produces a scanned beam of Class IIb intensity must have a safeguard to insure that upon failure the light level will not exceed Class IIb. Many dual-class products produce a lower light level in their scanning mode, but are certified for the higher output produced when the beam is stationary. CDRH did not require such products to have scanning safeguards in the past, although the language of the old regulations technically mandated it.

In any event, the new enforcement policy (which took effect immediately) will probably affect only laser light-show devices that produce both scanned and stationary laser beams. Similar dual-mode products are also used in the construction industry, but they are required to stay within the accessible emission limits of Class IIIa to begin with, and Class IIIa scanners don't need a failure safeguard.

David Lytle

Refractive Indices of Glasses at Laser Wavelengths

This data covers Schott Glass Technologies optical glasses and materials most frequently used in laser system applications. Index information on many other glass types is available from Schott and other major glass manufacturers.

WAVELENGTHS

	0.36501 μ m i line (Hg)	0.48613 F line (H)	0.53200 Nd $\div$ 2*	0.58929 D line (Na)	0.65627 C line (H)
SILICA	1.474540	1.463128	1.460707	1.458404	1.456369
BK7	1.536264	1.522377	1.519472	1.516728	1.514323
K5	1.544124	1.528600	1.525405	1.522411	1.519816
ED-4	1.586403	1.568597	1.565126	1.561900	1.559101
BAK4	1.594067	1.575897	1.572195	1.568740	1.565761
F2	1.666216	1.632083	1.625692	1.619892	1.615033
SK16	1.645590	1.627558	1.623826	1.620320	1.617273
SF12	1.701097	1.661868	1.654658	1.648143	1.642710
SF5	1.730549	1.687496	1.679618	1.672517	1.666612
SF15	1.764858	1.715459	1.706648	1.698749	1.692213
LAK8	1.745741	1.722220	1.717399	1.712885	1.708975
SF10	1.801748	1.746482	1.736734	1.728028	1.720849
SAPPHIRE	1.793570	1.775580	1.771764	1.768138	1.764943
SF11	1.874616	1.806455	1.794795	1.784458	1.775986

WAVELENGTHS

	0.69430 Ruby	0.84000 GaAs LED	0.90400 GaAs laser	0.94600 Nd — 2†	1.31800 Nd — 3†
SILICA	1.455427	1.452661	1.451704	1.451126	1.446722
BK7	1.513219	1.510024	1.508938	1.508288	1.503496
K5	1.518637	1.515291	1.514185	1.513533	1.508958
ED-4	1.557817	1.554065	1.552763	1.551974	1.545883
BAK4	1.564413	1.560624	1.559386	1.558661	1.553668
F2	1.612887	1.607085	1.605287	1.604263	1.597881
SK16	1.615885	1.611934	1.610623	1.609849	1.604384
SF12	1.640318	1.633884	1.631905	1.630780	1.623846
SF5	1.664019	1.657084	1.654968	1.653771	1.646546
SF15	1.689353	1.681738	1.679425	1.678118	1.670245
LAK8	1.707197	1.702154	1.700484	1.699499	1.692548
SF10	1.717715	1.709401	1.706888	1.705473	1.697038
SAPPHIRE	1.763468	1.759171	1.757698	1.756813	1.750190
SF11	1.772306	1.762610	1.759706	1.758078	1.748528

WAVELENGTHS

	1.06400 Nd-YAG	1.06000 Nd-Glass	0.63280 HeNe	0.35467 Nd $\div$ 3*	0.26600 Nd $\div$ 4*
SILICA	1.449640	1.449688	1.457020	1.476125	1.499680
BK7	1.506640	1.506693	1.515089	—	—
K5	1.511914	1.511965	1.520640	—	—
ED-4	1.549934	1.550000	1.559992	—	—
BAK4	1.556873	1.556929	1.566704	(Note: glasses do not transmit at these wavelengths.)	
F2	1.601841	1.601914	1.616556		
SK16	1.607921	1.607982	1.618241	—	—
SF12	1.628132	1.628212	1.644410	—	—
SF5	1.650977	1.651061	1.668457	—	—
SF15	1.675073	1.675165	1.694252	—	—
LAK8	1.697046	1.697124	1.710215	—	—
SF10	1.702188	1.702286	1.723086	—	—
SAPPHIRE	1.754553	1.754626	1.765963	1.796067	1.833063
SF11	1.754324	1.754436	1.778621	—	—

*Second, third and fourth harmonics of 1.064 μ m.

†Secondary Nd laser lines.

Diffraction Limited Lenses for Laser Applications

Uniform intensity distribution

When a lens system is irradiated at its aperture with a uniform intensity distribution, a diffraction pattern is formed at the focus. The pattern consists of a bright central spot surrounded by rings of rapidly diminishing intensity. The diameter of the central spot, known as the Airy disk, is approximated by this equation:

$$S = 2.44\lambda F/\#$$

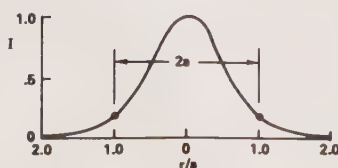


where s is the diameter of the central spot, λ is the wavelength of the source, and $F/\#$ is the ratio of the focal length to the lens aperture. In the absence of any lens imperfection, 84% of the energy is contained within the diameter s and the remainder is distributed in the outer rings. If a difference exists between the longest and shortest optical paths leading to a focus, a change in the size of the central spot as well as a redistribution of energy occurs. For an optical path difference of one quarter of the wavelength ($\lambda/4$), the size of the central spot is essentially unchanged, but there is a decrease of energy from the central spot to 68%. Traditionally, when this $\lambda/4$ limit on optical paths (known as the Rayleigh criterion) is not exceeded, the lens system is considered to be diffraction limited.

Gaussian intensity distribution

In the case of a lens system irradiated by a laser operating in the fundamental transverse mode (TEM_{00}), some flexibility is required in assigning a diffraction limited label to the lens system. The Gaussian distribution which describes the fundamental mode of a laser is given by the formula:

$$I(r) = \frac{2P_0}{\pi a^2} e^{-2r^2/a^2}$$



where P_0 is the total output power, $I(r)$ is the intensity at the distance r from beam center and a is the radius where the intensity falls to $1/e^2$ or 13.5% of the central intensity. The accepted beam diameter of the laser is defined as $2a$ and contains 86.5% of the total beam power.

Focusing of Gaussian beams

In the absence of aberration, a lens system irradiated by a Gaussian beam will form an image at its focus with an intensity distribution that is dependent on the ratio of lens aperture to the beam diameter $2a$. When that ratio is less than one, the focus will not be unlike the familiar Airy pattern. This is the result of the diffraction effect produced by radiation at the aperture boundary. As the aperture is increased, the diffraction effects are reduced and are virtually eliminated when the lens-aperture-to-beam-diameter ratio is made equal to or greater than $2.8a$. At this ratio the Gaussian distribution is preserved in the focal plane, and the corresponding focus spot is given by:

$$s = 1.27\lambda F/\#$$

where s is the diameter of the focus spot measured at the $1/e^2$ intensity points, λ is the wavelength of the source, and $F/\#$ is the focal-length-to-lens-aperture ratio.

In the presence of an optical path difference as great as one half wavelength ($\lambda/2$), the reduction in energy of the focus spot is less than 5%. The spot size is given as before by:

$$s = 1.27\lambda F/\#$$

so that $\lambda/2$ represents a perfectly satisfactory optical tolerance for image formation.

Collimation of Gaussian beams

The far field beam divergence of a Gaussian beam is given by:

$$\theta = \frac{2\lambda}{\pi a}$$

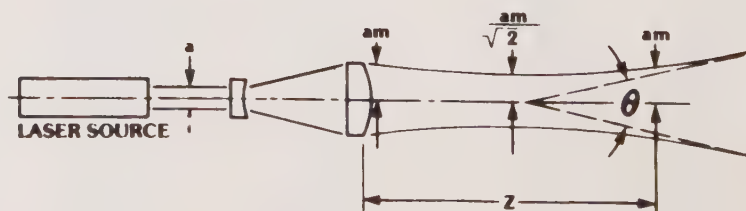
where θ is the full angle beam divergence measured at the $1/e^2$ intensity points, λ is the wavelength of the radiation, and a is the beam radius before propagation. For applications involving the illumination of distant objects, it may be necessary to reduce the beam divergence. By increasing a before transmission, a corresponding reduction in θ is realized. This is accomplished by a beam expander which yields a collimation range of:

$$z = \frac{\pi m^2 a^2}{\lambda}$$

where m is the expansion ratio of the beam expander and z is the range which produces equal $1/e^2$ beam radii measured directly at the output of the beam expander and at the end of the range. The beam profile along the z direction is illustrated in the schematic below.

This is basically equivalent to adding a weakly focusing lens system to the laser, and thus questions dealing with limiting aberrations and selection of appropriate lens apertures are identical to those involved in focusing of Gaussian beams.

—Joseph P. Machewirth
Special Optics



Designing with the HeNe Laser

The helium-neon (HeNe) laser has plenty to boast about. It offers excellence in size-to-power ratio, optical characteristics and reliability, universal availability, long life and low cost. The HeNe laser emits a visible (red) 632.8nm CW beam.

One of the major contributors to the HeNe laser's advantages is its conventional coaxial design (Figure 1). This structure lends itself to mass production and hence lower cost, and provides for easy mounting of the base tube in its housing. In addition, the coaxial design facilitates an even thermal distribution, which in turn means better stability in power and beam pointing, and ultimately longer life—often in excess of 20,000 hours.

The basic HeNe laser

Over the years, leading manufacturers have had outstanding success in standardizing the techniques required to secure desired results from the combination of elements that go into the HeNe laser. For this reason, any discussion about the characteristics and design of this laser type generally holds true for products from any of the leading manufacturers.

Most of our present HeNe lasers are of the hard-seal design. This means that the outer glass laser tube is fused at high temperature to the end electrodes. The mirrors are also hard-sealed at high temperatures, fused to precisely machined mirror holders for excellent angular beam alignment

and gas leak prevention. Hard-seal construction also facilitates high-temperature outgassing prior to final gas filling.

Let us consider the importance of the design and functions of the various elements of the laser tube. The resonator sits within the tube and consists of the capillary and the two end mirrors. Alignment of this resonator is very important to assure maximum power output. The combination of end mirrors (concave or plane) determines one of the three choices of resonator design—plane, confocal or hemispherical. Of these, the hemispherical (one concave and one plane mirror) is the most widely used, for two key reasons:

- higher production yields — while the resonator alignment is critical, hemispherical type resonators are more forgiving than plane or confocal types;

- lasers designed with hemispherical resonators can withstand shocks of greater intensity than other types while still performing to specs.

Capillary design

The capillary section of the laser tube has a precise, exceptionally straight bore to assure maximum power stability. There is a direct relationship between the bore diameter and length and the mirror geometry; this relationship must be carefully controlled to obtain the desired power range, beam diameter and divergence,

and mode purity. While the majority of capillaries are constructed of hard glass, soft glass or quartz can also be used. Hard glass is preferred, however, because of its lower cost and lower thermal coefficient of expansion. Considering the laser price/performance ratio, it offers the best of two worlds.

The design of the capillary is one of two basic types—bridge or cantilever. The cantilever design (Figure 2) requires the fusion of one end of the capillary to the laser's anode electrode and the placement of the other end's opening concentric to the cathode. This design is most appropriate for the shorter 1-2mW tubes. Because of their shorter length, capillaries in the smaller lasers are subject to less moment effect and therefore are better able to maintain a precision alignment. A cantilevered capillary is supported by a spider-shaped spring for additional ruggedness.

The bridge construction (Figure 3) is usually favored for longer tubes. Like the cantilever, it has one end fused to the anode electrode, but the other is precision fitted into a fixture so constructed as to allow for thermal expansion of the capillary. In a longer tube, bridge design is essential both to maintain resonator alignment in the face of shocks encountered in use and transport and to reduce power fluctuation due to rolling of the tube around its longitudinal axis. This design does not require spider spring support, but it does generally

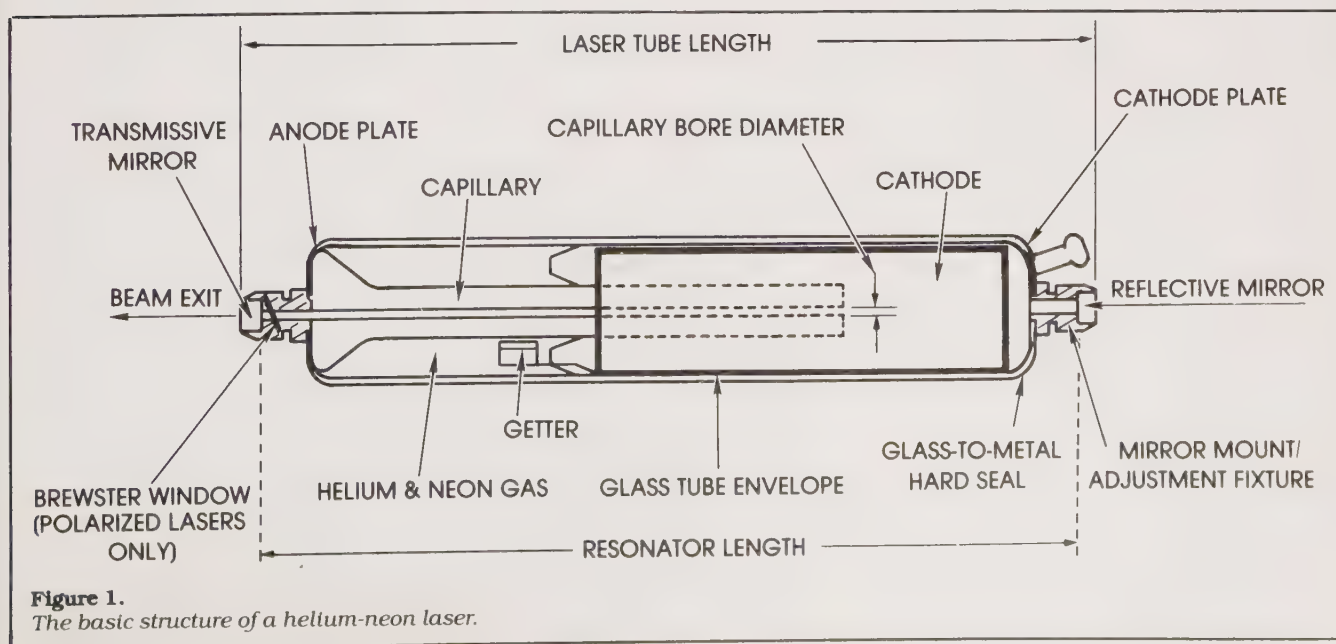


Figure 1.
The basic structure of a helium-neon laser.

require a hole placed in an appropriate position to facilitate replenishment of helium and neon gases.

Electrical and gas factors

The electrodes positioned at both ends of the laser tube are another important design element. The electrode type usually used with hard glass lasers is made of a metal called Kovar. Because Kovar's thermal coefficient of expansion is close to that of hard glass, its use reduces the chance of stress during periods of cooling and heating. To maintain cleanliness and avoid contamination, mirror mounts are brazed to the electrodes at high temperatures for added protection.

Aluminum alloy with 99 percent or more aluminum content is usually used for the cathode material. Other material, such as zirconium and barium, are also used, but are much more expensive. The aluminum surface area, its thickness, and its processing are all important factors that affect laser operating life. For maximum product life, it is critical to build a dielectric coating of even-thickness oxide layers on the cathode. This dielectric minimizes the absorption of helium atoms (trapped in the aluminum walls) and so maintains the correct gas ratios, an important factor in laser operation.

Other design factors play a part in gas purity. The hard-seal design of the contemporary laser tube enables degassing of the tube at higher temperatures (approximately 300°C) to obtain higher purity of final HeNe gases. With the higher temperatures, it is easier to remove gases trapped in the tube walls through just a few purging cycles. However, to maintain the purity of the gases during actual laser use, an essential factor for long operating life, designers have added a getter to the laser tube design. The getter facilitates removal of the last remaining contaminants from the glass, electrode and cathode walls. Normally, barium- or zirconium-based getters are used to attract any contaminants introduced in the plasma during laser use.

The optical elements

Like other elements of the laser tube, the mirror has gone through a design evolution accelerated by the greater understanding of material deposition gained through vacuum and semiconductor technologies. The dielectric coatings now employed are composed of multilayer stacks of alternating quarter-wavelength layers of titanium dioxide and silicon dioxide. Hard dielectric coatings are preva-

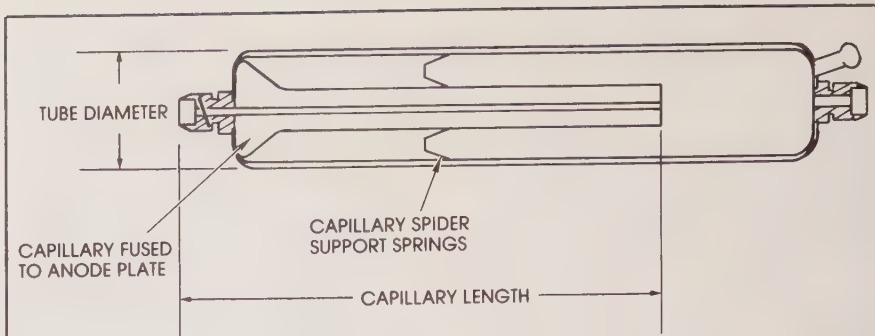


Figure 2.
The "cantilever" capillary design.

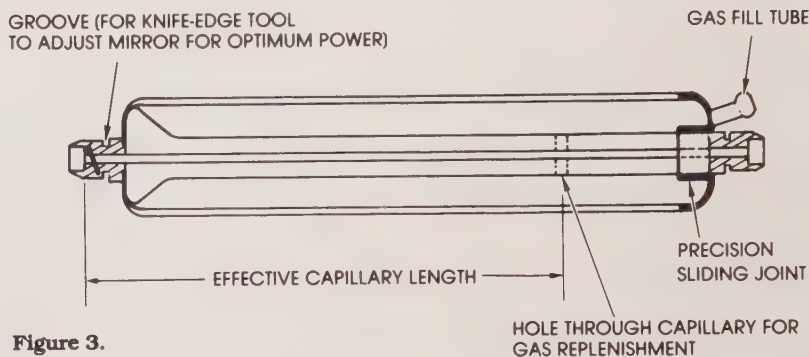


Figure 3.
The "bridge" capillary design.

lent, although soft coatings can be used. The material and thickness of the outermost layer must be nonreactive to prevent mirror reflectivity changes that can result in loss of power.

Brewster windows are employed to obtain a polarized beam. A single window on the beam output side is required for lasers with integrated mirrors. Typically, Brewster windows are made of quartz material and highly polished to minimize power loss. The windows are placed at Brewster's angle to obtain a polarized output beam. For lasers with external mirrors, particularly in the case of higher-powered HeNe types (10mW and over), two windows are used. These windows can be soft or hard sealed to contain the HeNe gases in the tube. The angle of the Brewster window in external mirror lasers must be aligned with great precision to maximize power through in-phase polarization.

Factors in success

No matter how good your basic HeNe laser tube is, the success or failure of an overall system hinges heavily on a variety of other factors. These include laser mounting techniques and hardware, electrical performance considerations, laser power supplies and the understanding of and ability to test certain laser parameters.

In general, commercial HeNe lasers are available as "raw" tubes or laser modules—suitable metal containers with laser tubes mounted within them by the laser manufacturer. If the user prefers to purchase laser tubes alone, he should follow a few common-sense rules for mounting them in his equipment. First of all, since a laser is a glass tube, care must be exercised not to overstress the glass envelope. Torsional or bending stresses may cause misalignment of the laser resonator that, however slight, will lead to reduced power output. A simple V-block with springs, capable of supplying enough pressure to hold the tube in place, can be used for mounting with good results in most cases.

To maintain the desired beam direction accurately, it is recommended that the laser tube be supported near both of its ends. Actually, since laser tubes are made from precision glass, one can support them at any point along their length, except *too* near the ends. This latter constraint stems from the fact that tube ends may be distorted during the high-temperature sealing process and consequently cannot serve as reliable position reference surfaces. Furthermore, one should leave sufficient space between the anode and the support to prevent the possibility of high-voltage arcing.

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Figure 4 illustrates some of these points.

A cost comparison

If a user elects to purchase a complete laser module, mounting problems become greatly simplified. Note that a typical laser module is a completely self-contained, rugged unit, ready to be plugged into a suitable power supply to produce a useful light output. Thus, in Siemens laser modules, the laser tube is firmly (but gently) held in position inside an aluminum housing by means of potting, such as Silastic®. This insures good shock resistance and directional stability over a wide range of temperatures. Beam alignment, concentricity and angular direction in such modules are typically $\pm 0.5\text{mm}$ and ± 0.5 milliradian, respectively, but tighter tolerances are also available.

While laser modules greatly simplify the mounting chore for a user, their cost is obviously higher than that of a raw laser tube. In deciding which choice is best, however, one must consider the *installed cost* of a laser in a system. That is to say, while the *component cost* of a laser tube is lower, it does not include the cost of suitable supports, the labor required for proper mounting and the higher degree of testing needed before a reliable system can be turned on and used. At the same time, don't forget that the cost of future replacement of the module will be higher than the cost of replacing a tube alone.

Electrical performance

To get both the maximum stable output from a HeNe laser and its typically long life, it is imperative that a laser system designer have a good understanding of pertinent laser electrical characteristics. First of all, to maintain the lasing process in the capillary bore of a laser, a constant DC current must flow through the device. Depending on the output power rating of the laser, this current may be anywhere between 3.25 and 14mA with a corresponding operating voltage range between 500 and 5000 VDC. Whatever the actual operating current level, it is a fixed value determined by the manufacturer during the design of each laser model. This means that the laser power supply must be a true current source.

Being a low-pressure gas device, the HeNe laser acts as a negative resistance from its firing voltage V_b to the operating voltage V_a . The high firing voltage is required to insure ionization of the gas, which must occur for lasing to happen. As soon as ionization occurs, the voltage across the laser rapidly diminishes to the

operating level (V_a). The V_b -to- V_a ratio is generally 6 to 10.

As lasing begins, the current flow through the laser is at its "break-current" level, just sufficient to ionize the gas. The current subsequently increases until it reaches its "operating-current" level.

The ballast resistor

To compensate for negative resistance effects, a ballast resistor is required. By connecting a suitable resistor in series with the laser anode, the overall laser device acts like a positive resistance load. The value of the ballast resistor is determined — and recommended — by the laser manufacturer. While its exact value is not very critical, it must be sufficient to ensure stable operation of the laser. In the case of a laser with an operating current of around 5mA, the ballast resistor can be anywhere from 60 to 90 kilohms.

The distance between the ballast resistor and the anode plate must be kept as small as possible, and most laser manufacturers' catalogs will specify the maximum distance permitted. In Siemens lasers, for instance, this distance is specified as not more than 50mm. The reason for keeping the ballast resistor as close as possible to the anode plate is to minimize its associated stray capacitance and, consequently, the capacitive impedance component. One should keep in mind that, at certain frequencies, this stray capacitance can reduce the overall ballast impedance. And such a shift in the ballast impedance may shift the break-current value closer to the operating current level, reducing laser stability and lifetime.

In placing the ballast resistor as close as possible to the anode plate, one should remember that the resistor will produce considerable heat. If it is necessary to maintain lower heat dissipation due to equipment requirements, the ballast resistor can be split in two — one resistor can be

mounted close to the anode plate, while the other can be placed some distance away.

Modulating laser output

The continuous-wave (CW) output of a HeNe laser must be modulated in numerous applications: for instance, in laser printing and optical data storage, the dot-dash matrix effect produced by selectively "turning the laser beam on and off." This is done, however, not actually by switching the laser beam on and off, but by selectively reflecting and returning the beam from and to its path. This is accomplished by acousto-optic modulators or "Bragg cells."

The basic operation of such a device is as follows. A suitable crystal (made from tellurium dioxide, for instance) has a layer of piezoelectric material bonded to one of its surfaces. When it is excited by an RF signal (typically at 100 or so megahertz for tellurium crystal), a train of acoustic square waves is set up within the crystal. Whenever the acoustic pulse is in its "high" level, an impinging laser beam is "turned off." When the pulse is at its "low" level, the beam is allowed to pass; that is, the beam is "turned on." By suitably timing pulses, virtually any modulation pattern can be achieved.

Tailoring the modulator to a specific wavelength is accomplished by adjusting the RF power input to the piezoelectric material. For instance, one acousto-optic modulator (the Model 3110 from Crystal Technology) has a spectral range between 0.44 and 1.20 μm . At 330mW RF power input, the corresponding wavelength is 0.442 μm . For a HeNe laser having the wavelength 0.6328 μm , the power input should be 700mW.

In general, acousto-optic modulators are available with RF frequencies in the gigahertz range. Thus, the laser system designer's selection is quite broad, resulting in practically unlimited freedom in considering a

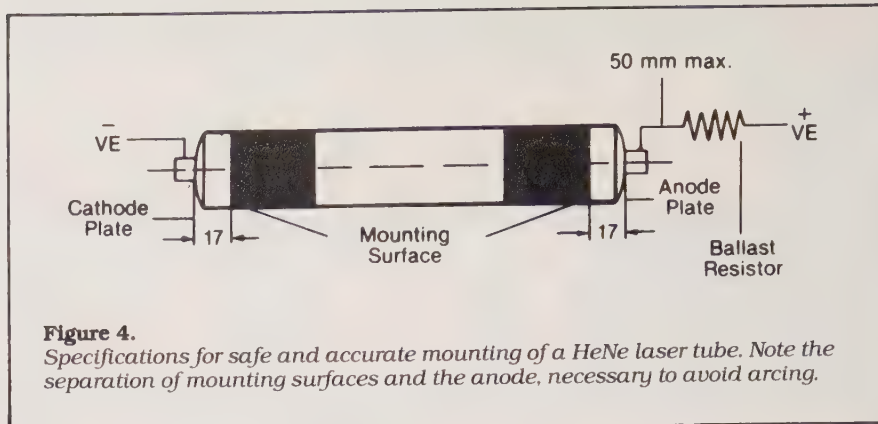


Figure 4.

Specifications for safe and accurate mounting of a HeNe laser tube. Note the separation of mounting surfaces and the anode, necessary to avoid arcing.

system for some specific applications. Such modulators can be readily obtained on the market today as neatly packaged "black boxes," alleviating the need for systems designers to know modulators' inner workings.

Laser power supplies

The power supply is undoubtedly one of the most critical components in any laser system. For proper laser operation, the power supply must completely match the laser characteristics, because if it doesn't, the laser will suffer reduced lifetime and will not be able to deliver its maximum undistorted rated power. Thus, if a laser is designed to operate at 5mA, the power supply must deliver 5mA, no more and no less.

In addition to its ability to put out a rock-stable operating current, a laser power supply must also meet some definite turn-on time. In other words, it must have the ability to develop the required firing voltage within a prescribed interval of time. In general, the rate of rise for the firing voltage is a question of cost.

The choice of a "fast" or "slow" power supply is totally application-dependent. Thus, in many handheld scanner applications, a fast turn-on time is a must — the laser must produce an output the moment the switch is depressed. On the other hand, in many applications where the laser stays on continuously, the power supply turn-on time is of no consequence. In certain applications, the US Bureau of Radiological Health requires a three-second delay in firing voltage. This feature is standard in conventional power supplies. Note that turning a laser on and off as often as desired has no detrimental effect upon its life.

In general, today's laser system designer can find a broad assortment of off-the-shelf laser power supplies. If only a single predetermined current is needed, relatively inexpensive power supplies are available. For experiments and testing of lasers, other power supplies with easily adjustable current outputs are used. And still other power supplies provide the capability of modulating current output and thus the associated laser light output. Each of these power supplies must comply with one or more standards, including UL in the US, VDE in Europe and CSA in Canada.

External optics

Most laser systems use some external optics, and because of the HeNe laser's relatively long history, the manufacturing technology for associated optics has moved close to perfection. Thanks to refinements in precise

and inexpensive coatings, today's reflectivities (when you need to reflect) and transmissivities (when you need to transmit) are excellent. For instance, we can depend on reflectivities of 99.9% in commercial-grade optics with surface flatnesses down to 1/20 of a wavelength. All these achievements contribute to better system performance, higher efficiencies, and lower power requirements.

Two major considerations affect the selection of mounting supports for external optics. One, of course, is the ease of adjustment and maintenance. The other is the ability of an optical train to establish and maintain the desired beam path. To this end, one must take into account temperature effects on the supports and the associated impact on the alignment among the various optical devices. This is particularly true in systems with long optical paths — e.g., for increasing the depth-of-field in optical data storage and reprographics.

Testing

Five key parameters must be tested to insure that a laser performs in accordance with its published specifications. These are: output power, beam diameter, beam position, operating voltage and break current.

- **Output power** — Output power measurements are extremely important. The amount of power produced by a laser frequently determines its ability to perform in a system. Also, accurate output power measurements are needed to check whether or not a given laser system conforms to the BRH requirements.

Crucial to proper output power measurement is the selection of a suitable light detector. While there are commercially-available power meters that can be used for this purpose, Siemens engineers prefer to use a meter designed specifically for the HeNe's 632.8nm wavelength output. One obvious reason for doing this is the fact that a typical off-the-shelf power meter tries to be all things to all people — each manufacturer strives to produce a product that serves the maximum number of users. In doing so, they can sacrifice accurate performance at a specific wavelength. At the same time, a test setup specifically designed to measure output power of HeNe lasers is relatively simple and can be built quickly and inexpensively.

- **Beam diameter** — As with the output power measurement, there are several techniques for obtaining beam diameter. A good comparison of several accepted and proved methods for beam measurement is pre-

sented in an article by LeRoy D. Dickson titled "Ronchi Ruling Method for Measuring Gaussian Beam Diameter," (*Optical Engineering*, Jan.-Feb. 1979, page 70). It provides a comparison among four methods — scanning pinhole, knife edge, variable-width scanning slit, and Ronchi rulings.

Whatever the measurement technique the user chooses, the object is the same — to obtain an accurate measurement at the least cost. To date, the Ronchi ruling method appears to produce the best results in terms of measurement accuracy and the amount of information on beam parameters — in addition to beam diameter, it also gives beam ellipticity and spatial noise.

- **Beam position** — Measurement of beam position determines the misalignment of the beam relative to the laser mounting surfaces. First, concentricity is checked by observing the spot produced by the beam near the laser output mirror. Next, to measure the angular alignment, the laser is rotated in a precision V-block and the circular path produced by the beam is recorded at a distance. The user can then determine whether or not the amount of misalignment is tolerable for his specific system. The radius of this circle, representing the alignment error, should be less than that specified. An "ideal" laser would produce a spot when tested in this way — i.e., a circle with zero radius.

- **Operating voltage** — To test operating voltage, the power supply is turned on and the laser operated for at least ten seconds. Next, the anode is touched with a high-voltage probe and the corresponding reading is observed on a multimeter.

- **Break current** — To measure the break current, a suitable ammeter is connected in series with the laser cathode. Then the laser is turned on and allowed to operate for five minutes at its rated operating current. Next, the current is decreased to the point where the laser discharge extinguishes. The current shown at the ammeter at this instant is the break current. To obtain an accurate value, it may be necessary to repeat this procedure several times and then average the readings.

Once a user formulates performance requirements for a laser-based system, his next chore is to match laser characteristics to these requirements. To this end, the user must know how laser manufacturers specify their products and what different parameters signify from an applications point of view. The first step in

TABLE 1. BUYER'S CHECKLIST OF MAJOR HeNe LASER PARAMETERS**OPTICAL PARAMETERS**

Output power at 632.8nm
(in milliwatts)
Minimum _____
Maximum _____

Total output power (all wavelengths)
Minimum _____
Maximum _____

Beam profile
Single-mode (TEM₀₀) _____
Multimode (TEM₀₁) _____

Beam diameter
_____ millimeters

Beam divergence
_____ milliradians

Beam polarization
Polarized _____ (Ratio=) _____
Random _____

Beam concentricity with temp.
_____ mm, over the range _____ °C

PHYSICAL PARAMETERS

Operating temperature range _____ °C
Storage temperature range _____ °C
Relative humidity range _____ %
Dimensions _____
Weight _____
Mounting provisions _____

ELECTRICAL PARAMETERS

Firing voltage _____ kilovolts
Operating voltage _____ kilovolts
Operating current _____ milliamperes
Break current _____ milliamperes
Power output 3 seconds after turn-on
_____ % of rated operating voltage
Ballast resistance _____ kilohms

SPECIAL REQUIREMENTS

this laser selection process, as with any product, is to study manufacturers' catalogs.

Table 1 lists parameters generally found in most HeNe laser specifications. We can divide them into three categories — optical, electrical and physical.

Optical parameters

The first optical parameter to consider is wavelength, which is, of course, 632.8nm in the case of the HeNe laser. As we have discussed before, the shorter the wavelength in a given system, the smaller the spot size that can be obtained. In such popular HeNe laser applications as optical data storage and reprographics, small spot size means higher storage and better resolution, respectively, than could be obtained from competitive laser types.

HeNe laser output power is usually specified in milliwatts (mW). To measure true *HeNe power* — i.e., output power at 632.8nm — one must use power meters sensitive to, and selective for, this wavelength. It is safe to assume that the user selects a HeNe laser for its ability to produce a certain output power at the 632.8nm wavelength, not at a combination of

wavelengths. Thus if the output power given in a manufacturer's specification represents the *total* output power for that unit, it may include other wavelengths, such as 339 and 115nm. Beware of confusing these parameters.

In examining the available output power, the user should also pay close attention to the way this parameter is defined in the manufacturer's specs. Manufacturers may define power as "maximum," "typical," "minimum" or not at all. For performance considerations, all of these terms except the minimum are rather meaningless, although maximum power is important for safety purposes. Obviously, a laser system designer is really interested in some minimum power level that he can get from a laser under all conditions. As for "typical" power output, what does it mean? When will the user get a "typical" unit and when will he get an atypical unit? And what will the variance from "typical" be? In short, a user is well advised to look over the output power specs to make sure that they say something meaningful, and that they are adequate for the overall system.

Another important consideration

affecting output power is whether or not the laser is single-mode (designated as TEM₀₀) or multimode (designated TEM₀₁). In a single-mode laser, output power has a classical Gaussian distribution as a function of the laser beam diameter — i.e., peak power occurs at the center of the beam. In a multimode laser, there are two power peaks at some distance from the center of the beam. The practical significance of this difference lies in the fact that power peaks in a multimode laser randomly rotate around the beam axis. This means that unless the optics can correct these shifts of power peaks, the laser output power will vary.

Beam characteristics

The next important optical parameter is the beam diameter. Generally, it is measured right at the output of the coupling mirror, although some manufacturers specify it on the *inner surface* of the coupling mirror. The latter is not very practical, since there is no way to measure it directly — one can only calculate inner-surface beam diameter on the basis of measurements obtained on the outside of the laser tube. In short, the user must acquaint himself

with the various possible techniques of measuring beam diameter and select the appropriate one.

In itself, beam diameter is not very significant, since practically any beam can be focused with appropriate optics. What is important, however, is the ability of a laser manufacturer to *maintain* a certain beam diameter in a given model. Once the designer is finished with the optics design, variations in beam diameter may play havoc with the laser output. Furthermore, beam diameter is important from the point of view of obtaining various system components (including the laser) from different sources. One obvious thing to do is to select beam diameters that are "industry standard," such as 0.75, 0.64, 0.49 or 0.85mm.

Beam divergence (specified in milliradians—mrad) is determined by the laser design and simply must be taken into account during the design of an optical train. Most standard mirrors for a particular beam diameter have standard divergence values.

Beam polarization is another optical parameter that one should consider. HeNe lasers are available with either polarized output, where the ratio of the two output planes is specified (typically 500:1) or with "random" polarization. Lasers with random polarization are generally preferable since they are less expensive than the polarized models and, for a given size, deliver more power because they have no loss due to the Brewster window required to produce polarization.

Electrical parameters

Most of the electrical parameters for a laser system are associated with its power supply. As noted above, such parameters as firing voltage (between 3 and 16kV), operating voltage *range* (between 600 and 2500 VDC), operating currents and break currents are important in system selection.

Power output of a laser immediately upon turn-on — i.e., the amount of output power available three seconds after the laser has been turned on — is of importance. There are numerous applications where lasers are required to deliver power immediately after turn-on. To meet this requirement, many HeNe lasers will deliver 80 percent or more of their rated output a few seconds after turn-on. Since more manufacturers don't specify this parameter, users should ask for it as part of a quote.

Power stability after warmup is a function of both laser design and the

laser power supply used. Consequently, one must consider power stability in conjunction with a particular power supply. One way to look at laser power stability is to view it as a ripple, rated in terms of a percentage of output power (typically $\pm 2.5\%$).

In general, a laser system designer must immediately define the required power supply and make sure it is available when selecting a laser for a particular system. For this reason, a user may very well consider the possibility of purchasing his power supply from the same source as his laser. But there are reliable manufacturers who specialize in supplies only.

Physical characteristics

Important physical characteristics of a HeNe laser include both mechanical and environmental factors, such as operating temperature (generally -25°C to 80°C), storage temperature (generally -40°C to 80°C), relative humidity (generally up to 95%), the ability to withstand a degree of shock, and the mounting requirements. Mounting is quite important in selecting a HeNe laser for a specific job — different manufacturers produce lasers with different mounting requirements. Thus, in considering

the possibility of purchasing lasers from a second source, mounting compatibility must be taken into account. In general, one should look for mounting that provides for ease of insertion and removal, and for the least amount of modification.

These are just the most common physical parameters needed for proper HeNe laser selection. In any specific situation, the user may require an in-depth analysis of one or more additional laser parameters to arrive at an optimum design solution. Coherence length of a laser is often among such parameters, yet is normally omitted from specifications. Another such parameter is beam pointing as a function of temperature. In this case, the reason for not specifying it in a general product catalog is that it is *temperature-range* dependent — i.e., the specification between 25 and 30°C differs from the number for the 15 to 30°C range.

Don't overlook the value of a plant visit to determine the suitability of a vendor. This gives the user a first-hand view of the supplier — how the lasers are manufactured, designed, modified and tested.

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Materials Processing Lasers

MANUFACTURERS' DATA ON CURRENT PRODUCTS

	Type	Aperture in mm	Divergence in mrad	Polarization	Line Power Efficiency/ Duty Cycle	Pulse Width in nsec (unless otherwise specified)	Pulse Shape	Pulse Repetition Freq in kHz (unless otherwise specified)	Energy per Pulse in Joules (unless otherwise specified)	Operating Time	Average Power in Watts (unless otherwise specified)	Peak-to-Peak Ripple in %	Safety Features (see code)	Auxiliary Equipment (see code)	Auxiliary Optics (see code)	Shop Derivative	CNC Capability
California Laser	CO ₂	1.6	8.5	ran or lin	6.5/100						7.5	2	e	b,p,s	g,n,o	✓	
Coherent	ND:Glass		<5			0.4 to 3msec		3pps	3 to 8				e	b	a	✓	✓
	Nd:YAG		<5 or <8			2 to 8 msec		24 msec	15mJ to 50J		4 to 6		e	t	n,p q,v	✓	✓
	CO ₂			lin						cont	to 3kW	2	e	u	a,q	✓	
Control Laser *multi	Nd:YAG		<10			0.65 to 4.0 msec	*see left	100 pps	80		400		a,b,d	b,s	i,n	✓	
	CO ₂	20	1.0			200 μ s to 200ns		1Hz to 1kHz			1.5 to 5kW	4	b	b,l,m	a,k,o,q,y	✓	✓
	Nd:YAG		0.3 to 10			100 to 600		1 to 40	0.1 to 60mJ	cont	2 to 600		h	b	a,i,n		
CVI Laser	Nd:YAG		0.2 or 3 TEM ₀₀	unpol						cont.	35 or 55	3	b,l,n		m,n		
Edinburgh Instruments	CO ₂	7.5	2	vert							50	1	b	w,x			
	CO ₂	1.3	10	vert			Gaus			>2500	4 or 8	1	b	y,z			
	CO ₂	4.4	4	hor or vert							3.5	1	b	b,g,w			
	CO ₂ /CO	7.5	2	hor							20/2	<1	b	w,x			

AUXILIARY OPTICS

- a. Focussing optics
- b. Unstable resonator
- c. Beamsplitters
- d. Gratings
- e. Polarizer
- f. Transfer optics
- g. Beam expander
- h. Engraving fields
- i. CCTV monitor
- j. Turning mirrors
- k. Focussing assemblies
- l. Attenuator
- m. Conversion optics
- n. Collimator
- o. Viewing system
- p. Frequency doublers
- q. Delivery optics

- r. Target beam
- s. Beam aligning system
- t. Positioning and parts handling
- u. Available (unspecified)
- v. Q-switch
- w. Harmonic generators
- x. Fiber optic illumination
- y. Beam bender

SAFETY FEATURES

- a. Shields
- b. Shutter interlock
- c. Microprocessor control
- d. Warning lights
- e. Meets BRH standards
- f. Class One compliance
- g. Enclosures

- h. Class IV compliance
- i. Pullbacks
- j. High voltage guard
- k. Coolant monitor
- l. Remote control
- m. Sealed laser head
- n. Overtemperature/no-flow interlock
- o. Radiation indicator

AUXILIARY EQUIPMENT

- a. Gold conversion kit
- b. Alignment laser
- c. Cutting nozzles
- d. CCTV
- e. X-Y-Z tables
- f. A/O attenuator
- g. Pumping and refill stations
- h. Remote controls

- i. Turnkey workstations
- j. Oxygen
- k. Spotting scope
- l. Energy meters
- m. Water chiller
- n. Pulser
- o. OEM modifications
- p. Programmable shutters
- q. Positioning equipment
- r. Power stabilizers
- s. Gas assist
- t. TV alignment
- u. Complete CNC capability
- v. Output conversion
- w. Beam profile monitor
- x. Alignment system
- y. PZT tuning
- z. Amplitude modulation

	Type	Aperture in mm	Divergence in mrad	Polarization	Line Power Efficiency/ Duty Cycle	Pulse Width in nsec (unless otherwise specified)	Pulse Shape	Pulse Repetition Freq in kHz (unless otherwise specified)	Energy per Pulse in Joules (unless otherwise specified)	Operating Time	Average Power in Watts (unless otherwise specified)	Peak-to-Peak Ripple in %	Safety Features (see code)	Auxiliary Equipment (see code)	Auxiliary Optics (see code)	Shop Derivative	CNC Capability
Electro Scientific	Nd:YAG		1	ran		<200		19.9			0.5				v		
	Nd:YAG		2	ran		140		19.9			3				v		
	Nd:YAG		1.25	ran		<40		19.9			0.7				l,n,v		
	Nd:YAG		0.6	lin		<60		19.9			0.1				v		
	Nd:YAG		1	ran		<70		19.9			1.75				v		
Ferranti	CO ₂	1.3	10	vert						>1 year	4	1	b,h	c,e,o	a		✓
	CO ₂	1.3	10	vert						>1 year	10	1	b,h	c,e,o	a		✓
	CO ₂	1.3	10	vert						>1 year	20	1	b,h	c,e,o	a		✓

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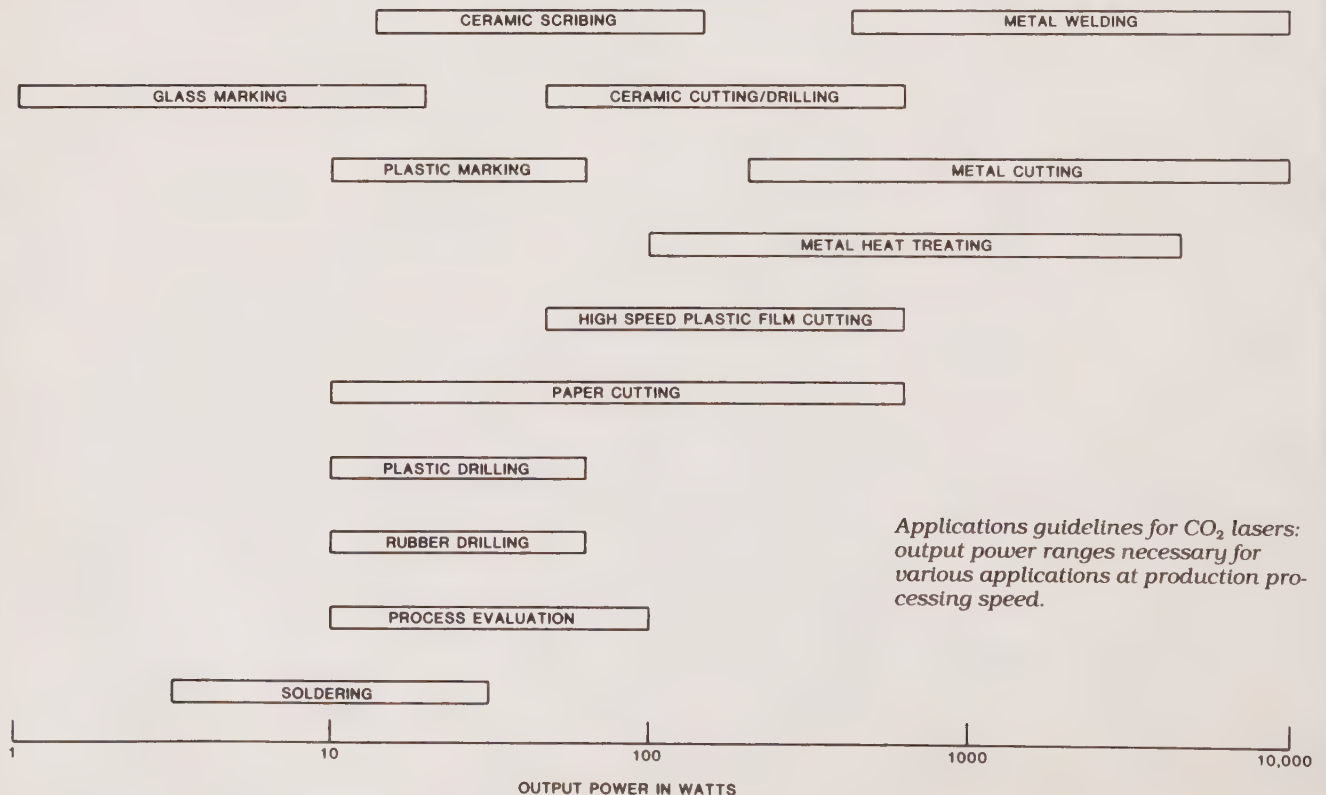
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Ferranti (cont.)	CO ₂	7.0	3	linear/ cir- cular	5%					cont	400	10	e,h	c,e, h,i	a,e, k,y		✓
	CO ₂	11.0	2	linear/ cir- cular	5%					cont	1100	10	e,h	c,e, h,i	a,e, k,y		✓
	CO ₂	45	2	linear/ cir- cular	5%					cont	4500	10	e,h	c,e, h,i	a,b, q,s		✓
	CO ₂	45	2	linear/ cir- cular	5%					cont	10000	10	e,h	c,e, h,i	a,b, m,q,s		✓
Florod Corp.	Xenon/ Nd:YAG					50ms		60Hz	.025				f	b	f,g		✓
Helionetics	Excim/ XeCl	3	<2	ran	1/100	50	sq	100 pps	1	cont	100	1	a,b,c		a,b		✓
JEC Lasers	Nd:YAG		10 or 15		10 to 30	< 20ms		<2	<55		3 to 100	0.14	b,g	b,c, d,q	h,n,r	✓	✓
J.K. Lasers *programmable	Nd:YAG/ Nd:glass		1 to 20	ran	4/100	0.1ms to CW	*see left	<200 Hz	<100				b,g	b,c,s	i,n,x		✓
Laakmann Electro-Optics	CO ₂	1.6	8	lin or vert	8/100	50μs	sq	5			20	3	b	b,q	a,n		
Lambda Physik	UV Excim	8 × 25mm	2 × 4		2	20		250Hz	1		100						
	Excim	10 × 25	4		2	15 to 25	tri	250Hz	150 to 400mJ								
Lasag AG	Nd:YAG	6 or 9	3 to 5	ran		0.1 to 20ms	rect	< 300Hz	1 to 80		30 to 300	2	a,b,d	j,x	u,w		✓
Laser Applications	CO ₂	4	5	lin						cont		5	b	b	a,n		
*Spike & tail	CO ₂	25	9			2μs	*see left	.02	3				b		a,n		
Laser Engineering	CO ₂	3.4/3.6	4.1/3.9	ran or pol		30ms to 1s	rect	1pps	10 to 35	cont	<35	2	b,k,o	b,d	q		✓
	CO ₂	4.5	3.2	ran or pol		30ms to 1s	rect	1pps	50	cont	<50	2	b,k,o	b,d	q		
	CO ₂	6/6.5	2.4/2.2	ran or pol		30ms to 1s	rect	1pps	75 or 100	cont	75 or 100	2	b,k,o	b,d	q		✓
Laser Inc.	Nd:glass		<5		4	<8ms		3pps	60				h	b,l	n,q	✓	✓
*leading edge spike	CO ₂			lin	15/100		*see left	to 2.5		cont	50 to 750		h	c,l	e,g	✓	✓

	Type	Aperture in mm	Divergence in mrad	Polarization	Line Power Efficiency/ Duty Cycle	Pulse Width in nsec (unless otherwise specified)	Pulse Shape	Pulse Repetition Freq in kHz (unless otherwise specified)	Energy per Pulse in Joules (unless otherwise specified)	Operating Time	Average Power in Watts (unless otherwise specified)	Peak-to-Peak Ripple in %	Safety Features (see code)	Auxiliary Equipment (see code)	Auxiliary Optics (see code)	Shop Derivative	CNC Capability
Laser Inc. (cont.)	Nd:YAG		<5	ran	4		Gaus	<80			25 to 100		h	b,e	q	✓	✓
Laser Industries	Nd:YAG/ Ruby	3/8"				0.4 to 5ms		6pps	60				b,e	j,k	i	✓	✓
Line Light Laser Corp.	CO ₂		<3.5	vert							10		b		a,l		
MBP Technologies	CO ₂	5.9	3.5	lin	8.2					cont	14 TEM ₀₀	2	a,b,m	m,r	q		
McMahan Associates	CO ₂		0.5	ran	10	2 to 500ms	TEM ₀₀	5000 Hz	500mJ	cont	3kW	0.5	e	b,d,e	q	✓	✓
Oxford Lasers	Cu VAP	44	3	unpol	1	20-60	tri	7	8mJ		40		b,d	a	b,c		
Photon Sources	CO ₂		3	ran	100					cont	1250 or 2500	5	a,b	b,q	q	✓	✓
	CO ₂		2	ran	100	>50μs	vary	1500 Hz	vary	cont	125	5	a,b	b,q	q	✓	✓
	CO ₂		2.5	ran/ lin/ circ	100	50 to 100μs	vary	1500 Hz	vary	cont	450	5	a,b	b,q	q	✓	✓
	CO ₂		3	lin or circ	100	100μs	vary	1000 Hz	vary	cont	1100	5	a,b	b,q	q	✓	✓
PI Lasers	CO ₂	3	4.5	lin or ran	3	0.1 to 1000 ms	rect	1 to 1000 Hz		cont	3 to 50	5	b,e,l	b	k	✓	✓
Plasma Kinetics	Cu/Ag		12 or 2	unpol	0.2 to 0.8	30		5	2 to 8mJ				b,e		b,c,e		
Quantronix Corp.	Nd:YAG		1.5-5.0 (●cm) 0.15 TEM ₀₀	unpol vert		90 to 250	Gaus	<50	1 to 16mJ	cont	6-18 TEM ₀₀ to 150 (mm)	5	b,n		n,w	✓	✓
Quantel	Nd:YAG		0.7	lin		35ps to 10	Gaus	100Hz	1 to 70				a,b	b			
Raytheon	CO ₂	1.4	2	ran		0.1 to 99.9ms	*see left	2		>95	600		b,d,j	m,n,o	a,e,j,n	✓	✓
* leading edge spike	Nd:YAG		5-10 (●cm)	ran		1 to 10ms	trap	10Hz	50				b,d	h,i	i,k,n,q	✓	✓
	Nd:YAG		10-20 (●cm)	ran		0.13 to 7μs	trap	200Hz	50				b,d	i,n	i,k,n,q	✓	✓
	Nd:YAG		5 to 10 (●cm)	ran		1 to 10ms	trap	10Hz	20				b,d	h,i	i,k,n,q	✓	✓
Spectra-Physics	CO ₂	13	2			100μs		1 to 2500 Hz			600		b,n	b,c	a,e,k, n,y	✓	✓

	Type	Aperture in mm	Divergence in mrad	Polarization	Line Power Efficiency/ Duty Cycle	Pulse Width in nsec (unless otherwise specified)	Pulse Shape	Pulse Repetition Freq in kHz (unless otherwise specified)	Energy per Pulse in Joules (unless otherwise specified)	Operating Time	Average Power in Watts (unless otherwise specified)	Peak-to-Peak Ripple in %	Safety Features (see code)	Auxiliary Equipment (see code)	Auxiliary Optics (see code)	Shop Derivative	CNC Capability
Spectra-Physics (cont.)	CO ₂	19	1.4	lin							1500		b,c	b,c	a,e,y		✓
	CO ₂	44	3								2500 or 5000		b	b,c	a,y		✓
Tachisto	CO ₂	.75 x 1.5				80	rect	0.1 to 120Hz	0.2 to 5				a,b		b,d		✓
	Excim		2x6			15 to 35	rect	0.1 to 120Hz	0.2 to 5				a,b		b		✓
US Laser	Nd:YAG		1.4 to 2								18 TEM ₀₀ to 150 (mm)		b,f	q,s	a,i,n, q,v		✓
Vuman	lod		<2	vert	10	15 to 30	Gaus	5ppm	1-5				b	b	g,v		
	lod	22 or 16	2	unpol	0.6	2μs to 30μs		6ppm or 1Hz	3				a,b	b,s	a,r		

Carbon Dioxide Lasers: Applications vs. Power



*Applications guidelines for CO₂ lasers:
output power ranges necessary for
various applications at production pro-
cessing speed.*

Communications Diode Lasers

MANUFACTURERS' DATA ON CURRENT PRODUCTS

	Active Material	Central λ / λ Range (nm)	CW/Pulsed	Rated Output Power (mW)	Rise Time (nsec)	Turn-On/Off Delay Time (nsec)	CW Spectral Line Width (nm)	Typical Threshold Current (mA)	Multimode or Single-Mode	Internal/External Cooler Type	Operating Temperature (°C)	Package Type (DIL = Dual In-Line)	Applications/ Comments
Amperex	GaAlAs	850	CW	3	0.5	0.5	3	75	M	NA	30-60	SOT-148	with 50/125 fiber pigtail; other pigtails available
Anritsu America	InGaAsP	1300	CW	>20	0.5		4	60	M	external APL1300	0-50	open package	high-frequency, long-haul communication
Diolite	GaAlAs	770-850	CW	3.5	<10		<1		S	internal TE	5-40	NA	free-space communication
Fermionics	InGaAsP	1300	CW	10	0.5		3	20-40	S	internal TE	-20-+60	14 pin DIL or heat sink	communication
Fujitsu	InGaAsP	1300	CW	5	0.5		2	20	M	external FLD130 D1WJ	-40-+50	modified TO-18	long-haul optical communications
	InGaAsP	1300	CW	5	0.5		2	20	M	external FLD130 D1WK	-40-+50	modified TO-5	long-haul optical communications
	InGaAsP	1300	CW	1.6	0.5		2	20	M	external FLD130 D1JM	5-50	with pigtail	long-haul optical communications
	InGaAsP	1300	CW	5	0.5		2	20	M	external FLD130 D3SJ	-40-+50	chip on carrier	long-haul optical communications
General Optronics	GaAlAs	800-850	CW	3	5		15	100	M	internal TE	-40-+65	DIL	CATV, local analog transmission
	GaAlAs	800-850	CW	3	1		2	80	M	internal TE	-40-+80	DIL	CATV, local telephone
	InGaAsP	1300	CW	1	1		3	60	S	internal TE	-40-+80	DIL	long-haul telephone, CATV supertrunk
	InGaAsP	1300	CW	3	1		3	60	M	internal TE	-40-+80	DIL	long-haul telephone, CATV supertrunk
Lasertron, Inc.	InGaAsP	1280-1320 1180-1220	both	>1.0	<0.5	<0.4	<4.4	40	S	internal TE	-10-+65	14 pin DIL	telecom trunking
	InGaAsP	1500-1560	both	0.25	<0.5	<0.4	<4.4	40	S	internal TE	-10-+65	14 pin DIL	telecom trunking
	InGaAsP	1500-1560	both	1.0	<0.5	<0.4	<5.5	40	M	internal TE	-10-+65	14 pin DIL	telecom, development
	InGaAsP	1280-1330	both	>2	0.5	<0.4	<4.4	40	M	internal TE	-10-+65	14 pin DIL	telecom
	InGaAsP	1290-1330	both	1	0.3	<0.4	<3.3	40	S	internal TE	-10-+65	14 pin butterfly	experimental, long haul
M/A-Com Laser Diode	GaAs	850 CW, 850, 904, 1300 pulsed	both	7CW, 1-1000 pulsed	1	1	3	50	both	Peltier	-40-+60	coax, DIL, flat	local loop, CATV, datacom, data bus

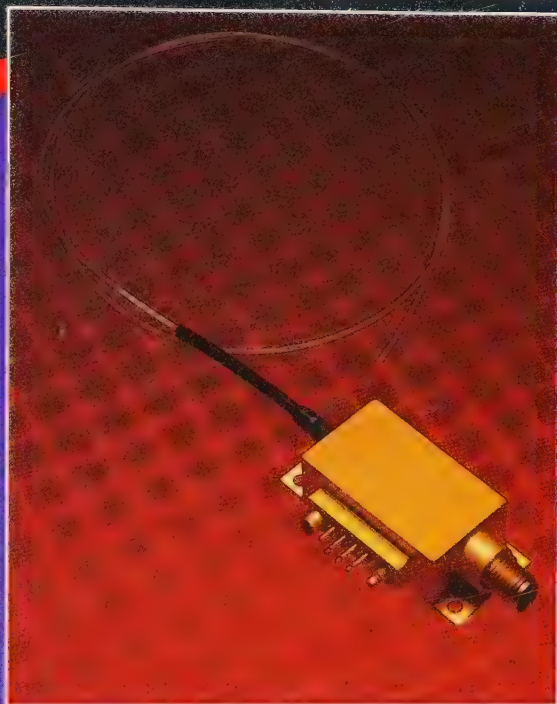
	Active Material	Central λ / λ Range (nm)	CW/Pulsed	Rated Output Power (mW)	Rise Time (nsec)	Turn-On/Off Delay Time (nsec)	CW Spectral Line Width (nm)	Typical Threshold Current (mA)	Multimode or Single-Mode	Internal/External Cooler Type	Operating Temperature ($^{\circ}$ C)	Package Type (DIL = Dual In-Line)	Applications/ Comments
Mitsubishi Electronics	InGaAsP	1300	CW	1.5	<0.5			20 at 25 $^{\circ}$ C	S	NA	+5-50	FU-41SLD	long-haul to medium-distance telecommunications
	InGaAsP	1300	CW	2	<0.5			20 at 25 $^{\circ}$ C	M	NA	-20-+60	FU-31LD	long-haul, local loop, CATV supertrunking
	AlGaAs	850	CW	3.2				30 at 25 $^{\circ}$ C	M	NA	-20-+50	FU-21LD	long-haul and short haul, datacom
	AlGaAs	780	CW	3	<0.5			30 at 25 $^{\circ}$ C	both	NA	-40-+60	ML-4000 series	low-cost source for datacom, LAN
	AlGaAs	815	CW	3	<0.5			30 at 25 $^{\circ}$ C	S	NA	-40-+60	ML-3000	low-cost communication link
NEC Electronics	GaAlAs	780	CW	5.0			1.0 half power	50	S	NA	-10-+70	NEC	Digital audio disk, video disk optical head, non-impact laser printer
	GaAlAs	780	CW	10			NA	50	S	NA	-10-+70	NEC	
	InGaAsP	1300	CW	3	0.5	1.0	4.0	20	M	internal TE	-20-+65	14-pin DIL	long distance, high-capacity transmission systems
	InGaAsP	1200	CW	2.5	0.5		4.0 max.	25	M	internal TE	-20-+60	14 pin DIL	long-distance, high-capacity transmission systems
	InGaAsP	1300	CW	1.5	0.5		4.0 max	20	S	internal TE	-20-+65	14 pin DIL	long-distance, high-capacity transmission systems
	InGaAsP	1300	CW	1.5	0.5		4.0 max.	20	S	internal TE	-20-+65	14 pin DIL	long-distance, high-capacity transmission systems
	GaAlAs	850	CW	8	0.5	0.5	2 half power	100	M	NA	-40-+70	NEC	long-haul telephone communication, CATV
	GaAlAs	850	CW	2	0.5	0.5	2 half power	100	M	NA	-40-+70	NEC with pigtail	long-haul telephone communication, CATV
	GaAlAs	850	CW	5	0.5	0.5	1 half power	65	S	NA	-40-+70	NEC	high-speed, long-distance telephone communication & CATV
	InGaAsP	1300	CW	5	0.5	0.7	4 half power	20	M	NA	-40-+70	NEC	long-distance, high-capacity telecommunication
	InGaAsP	1300	CW	8	0.5	0.7	4 half power	20	M	NA	-40-+70	chip on carrier	long-distance, high-capacity telecommunications
	InGaAsP	1300	CW	8	0.5	0.7	4 half power	20	M	NA	-40-+70	chip on carrier with monitor diode	long distance, high-capacity telecommunications
	InGaAsP	1300	CW	2.5	0.5	0.7	4 half power	20	M	NA	-40-+70	NEC with pigtail	long-distance, high-capacity telecommunications

	Active Material	Central λ / λ Range (nm)	CW/Pulsed	Rated Output Power (mW)	Rise Time (nsec)	Turn-On/Off Delay Time (nsec)	CW Spectral Line Width (nm)	Typical Threshold Current (mA)	Multimode or Single-Mode	Internal/External Cooler Type	Operating Temperature ($^{\circ}$ C)	Package Type (DIL = Dual In-Line)	Applications/ Comments
NEC Electronics (Continued)	InGaAsP	1300	CW	1.5	0.5	0.7	4	20	M	internal TE	-20- +65	NEC with single- mode pigtail	high-capacity, long-distance transmission
	InGaAsP	1300	CW	1.5	0.5	0.7	4	20	M	NA	-20- +65	NEC with single- mode pigtail	high-capacity, long- distance transmission
	InGaAsP	1300	CW	1.5	0.5	0.7	4	20	M	internal TE	-20- +65	14 pin DIL with single- mode pigtail	high-capacity, long- distance transmission
Newport Corp.	GaAlAs	850- 904	pulsed	1000 (peak)	<100	<1		>1000	M	NA	15- 35	hermeti- cally sealed	photodetector re- sponse character- ization, fiber OTDR, light source for laser ranging systems
Opto-Electronics	GaAlAs	850	pulsed	30 (peak)	0.04		NA	NA	M	NA	25	own	pulse-dispersion testing of optical fibers
	InGaAsP	1300	pulsed	30 (peak)	0.04		NA	NA	M	NA	25	own	pulse-dispersion testing of optical fibers (single-mode and multimode)
	InGaAsP	1500	pulsed	1 (peak)	0.1		NA	NA	M	NA	25	own	pulse-dispersion testing of optical fibers (single-mode)
	GaAlAs	810- 870	pulsed	100 (peak)	0.05		NA	NA	M	NA	25	own	pulse-dispersion testing and high- speed photodiode testing
	GaAs	904	pulsed	200 (peak)	0.05		NA	NA	M	NA	25	own	high-resolution, short-distance OTDR
	InGaAsP	1160- 1350	pulsed	5 (peak)	0.07		NA	NA	M	NA	25	own	pulse-dispersion testing of optical fibers
Ortel	GaAlAs	820- 860	CW	3 & 10	0.1		<0.005	10	both	NA	0-50	heatsink, pigtailed	high-speed, high- frequency (DC-6GHz) data or signal transmission
	GaAlAs	820-860	CW	10	0.15		<0.01	25	S	NA	0-50	open heatsink	optical disk, distance measurement, free- space communica- tion, laboratory instrumentation
	GaAlAs	820-860	CW	10	0.15		<0.01	25	S	NA	0-50	optical mount	microwave transmission, free- space communica- tion, picosecond pulse source
	GaAlAs	820-860	CW	3	0.15		<0.01	25	S	NA	0-50	fiber pigtail	transmission of high-frequency signals for broad- band communica- tions, high-speed data channels, radar IF transmission

	Active Material	Central λ / λ Range (nm)	CW/Pulsed	Rated Output Power (mW)	Rise Time (nsec)	Turn-On/Off Delay Time (nsec)	CW Spectral Line Width (nm)	Typical Threshold Current (mA)	Multimode or Single-Mode	Internal/External Cooler Type	Operating Temperature ($^{\circ}\text{C}$)	Package Type (DIL = Dual In-Line)	Applications/ Comments
Ortel (Continued)	GaAlAs	820-860	CW	10	0.07		<0.01	20	S	NA	0-50	optical mount	microwave, transmission, free-space communication, picosecond pulse source
	GaAlAs	820-860	CW	3	0.07		<0.01	20	S	NA	0-50	fiber pigtail	microwave transmission conventional radar, phased array radar, signal processing
	GaAlAs	820-860	CW	3	0.15		<0.01	15	S	NA	0-50	open heatsink	optical disk, distance measurement, free-space communications, laboratory instruments
	GaAlAs	820-860	CW	3	0.15		<0.01	15	S	NA	0-50	optical mount	microwave, transmission, free-space communication, picosecond pulse source
	GaAlAs	820-860	CW	1	0.15		<0.01	15	S	NA	0-50	fiber pigtail	transmission of high-frequency signals, broadband communication, high-speed data channels, radar IF transmission
	GaAlAs	820-860	CW	3	0.07		<0.01	10	S	NA	0-50	optical mount	microwave transmission, free-space communication, picosecond pulse source
	GaAlAs	820-860	CW	1	0.07		<0.01	10	S	NA	0-50	fiber pigtail	transmission of microwave signals, conventional radar, phased array radar, signal processing
	GaAlAs	820-860	CW	3	0.15		<1.5	15	M	NA	0-50	open heatsink	low-noise communications, free-space communications, laboratory instrumentation
	GaAlAs	820-860	CW	3	0.15		<1.5	15	M	NA	0-50	optical mount	low-noise communications, free-space communications
	GaAlAs	820-860	CW	1	0.15		<1.5	15	M	NA	0-50	fiber pigtail	low-noise communications, transmission of high-frequency signals, broadband communications, high-speed data communications, radar IF transmission
Philips Elcoma	InGaAsP	1300		2	0.5		1 at 50% 4 at 10%	25		503CQF	0-6	modified SOT-148	long-distance, high-speed communications and data transmission

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	Active Material	Central λ / λ Range (nm)	CW/Pulsed	Rated Output Power (mW)	Rise Time (nsec)	Turn-On/Off Delay Time (nsec)	CW Spectral Line Width (nm)	Typical Threshold Current (mA)	Multimode or Single-Mode	Internal/External Cooler Type	Operating Temperature ($^{\circ}\text{C}$)	Package Type (DIL = Dual In-Line)	Applications/ Comments
Philips Elcoma (Continued)	InGaAsP	1300		3	0.5		1 at 50% 4 at 10%	25		502CQF	0-60	modified SOT-148	long-distance, high-speed communications and data transmission
Spectra Diode Laboratories	GaAlAs	780-870	pulsed	500	0.5	<1.0	2	250	M	NA	70	TO-18 fiber	illumination, communications, data transmission, multipoint beamsplitting, optical excitation
	GaAlAs	780-870	pulsed	1000	0.5	<1.0	2	250	M	NA	70	TO-18 window	illumination, communications, fiber transmission, optical excitation
	GaAlAs	780-840	CW	100	0.5	0.5	2	250	M	NA	70	open heat sink	illumination, fiber transmission, communications, printing, optical excitation
	GaAlAs	780-840	CW	100	0.5	0.5	2	250	M	NA	70	TO-3 window	illumination, fiber transmission, datacom, printing, optical excitation
	GaAlAs	780-840	CW	50	0.5	0.5	2	250	M	NA	70	TO-3 fiber coupled	fiber data & power transmission, optical excitation, multipoint beamsplitting
	GaAlAs	780-840	CW	20	0.3	0.3	2	90	S	NA	70	open heat sink	printing, optical recording, illumination, fiber transmission, optical scanning, optical excitation
Stantel	GaAlAs	850	CW	2	0.5		3	70	M	internal LC30-19	-30- +65	DIL	analog, CATV
	InGaAsP	1300	CW	1	0.5		3	100	S	internal LC51-19	-40- +70	DIL	long-haul
	InGaAsP	1300	CW	1	0.5		3	100	S	external LC53-17	-10- +70	6-pin L-line	long-haul
	InGaAsP	1300	CW	1.5	0.5		3	100	M	external LC50-17	-10- +70	6-pin L-line	long haul, local loop
	InGaAsP	1300	CW	1.5	0.5		3	100	M	internal LC52-19	-40- +70	DIL	long-haul, local loop
Telefunken	GaAlAs	790-850	CW	5/10/20	1		1.5	80-100	M	TXAC/ TXAD/ TXAF 7900- 8500	0-65	SOT-148	optical storage
	GaAlAs	790-850	CW	10/20	1		1.5	80-100	M	TXSD/ TXSF 7900- 8500	0-65	open heat sink	fiber gyro
	GaAlAs	790-850	CW	10/20	1		1.5	80-100	M	TXTD/ TXTF 7900- 8500	0-65		telemetry, military
	GaAlAs	790-850	CW	5/10/20	1		2.5	100	M	internal Peltier TXBD 8500	0-65	TO-3 header	optical pulse generators



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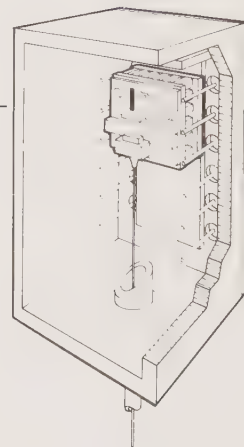
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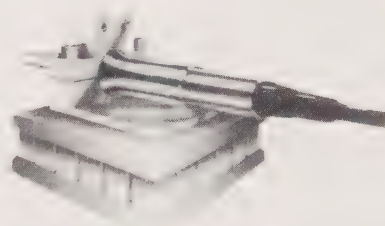
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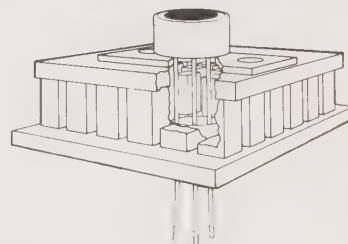
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Designing an Argon Laser System

While argon lasers have been around for a long time, they have only recently moved from the highly controlled laboratory environment into the rough-and-tumble of scientific and commercial applications. What made this transition possible was the advent of internal (integrated) mirror designs. By integrating the mirrors with the laser tube, designers have made argon lasers compact, rugged, self-contained, and just as easy to use as the familiar HeNe units.

The success or failure of an argon-laser-based system depends heavily on a thorough understanding of certain mechanical, electrical and environmental requirements that must be met if the system is to achieve its main design goal: reliable performance over its rated life of about 10,000 hours. With this in mind, we will review some of the factors that the system designer must take into consideration when designing an argon laser into equipment. Our purpose will be to aid OEM designers who work on equipment that is going to be produced in volume, sold the world over and subject to periodic servicing (since even lasers don't last forever).

The basic argon laser is a combination of mechanically and optically precise components. Like other laser types, it requires three primary elements: a lasing medium that can be excited to yield photons in a confined space, a power supply to activate the lasing medium, and a resonator to facilitate light amplification. The lasing medium is argon gas that produces a distinctive blue-green beam

in the 476–514nm wavelength range. The beam is thus visible and can be focused to a very small and sharp spot.

Present argon lasers are of the hard-seal design: all glass-to-metal and ceramic-to-metal joints are fused together at high temperatures (in contrast to soft-seal gluing). The mirrors are also hard-sealed at high temperature and fused to precisely machined mirror holders for excellent angular beam alignment and gas leak prevention. Hard-seal construction facilitates high-temperature outgassing prior to final gas filling. This results in a contaminant-free environment for the lasing medium, which contributes to a longer operating and shelf life.

Let us consider the importance of the design and functions of the various elements of the argon laser. At its heart is the resonator — an insulator/capillary and two end mirrors. The insulator material in an argon laser is generally beryllium oxide (BeO) because of its physical properties, particularly its ability to conduct heat rapidly. Argon laser manufacturers continue to experiment with lower-cost materials, hoping to improve laser performance and reduce costs, but BeO is still the choice.

In addition to being able to withstand high operating temperatures and to conduct heat efficiently, the insulator must provide good electrical insulation. This is because an argon laser is highly inefficient in the sense that about 95 percent of its electrical input energy is lost in the form of heat. Another requirement is

that the insulator must not introduce contaminants into the lasing medium at high temperatures.

Mirror design

The mirror design is equally important. Figures 1a and 1b schematically compare integrated and external mirror designs. Referring to Figure 1a, note the compact construction made possible by the integrated-mirror design. This is attributable to the development of high-temperature sealing methods, permitting the use of reliable glass-to-metal and ceramic-to-metal seals that can tolerate wide temperature swings. Before the development of the integrated-mirror technology, mirrors would be mounted externally to the laser cavity, as in Figure 1b. This required a complex, individually machined and expensive Invar rod frame to maintain mirror-resonator alignment. Invar's thermal coefficient of expansion is within tolerable limits to permit axial alignment of the resonator over the operating temperature range, but these external-mirror lasers are sensitive to shock. This can lead to resonator misalignment which, in turn, will lead to a loss of optical power output.

With integrated mirror technology, the argon lasers became compact and lighter, and the resonator alignment became less sensitive to shock and vibration. This has enabled designers to consider the use of air-cooled argon lasers in portable equipment now under development to take advantage of their small size and lower production costs.

Like other elements of the laser

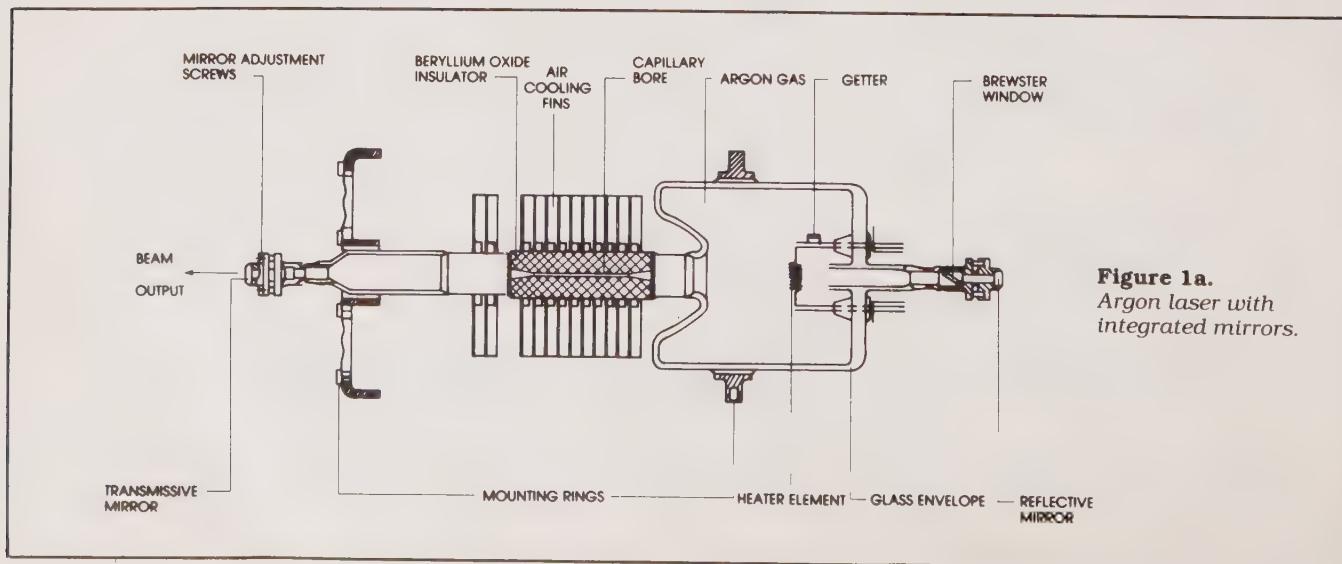


Figure 1a.
Argon laser with
integrated mirrors.

tube, mirrors have gone through a design evolution accelerated by the greater understanding of material deposition gained through vacuum and semiconductor technologies. The dielectric coatings now employed are composed of multilayer stacks of alternating quarter-wavelength layers. Hard dielectric coatings are prevalent, and Brewster windows are used to obtain a polarized beam. These are made from quartz material and are highly polished to minimize power loss. The windows are placed at Brewster's angle to obtain a polarized output beam.

Turning our attention to the design of the second resonator component, the capillary, one should note the direct relationship between the bore diameter and length and the mirror geometry. The relationship must be carefully controlled to obtain the desired output power range, beam diameter and transverse electric mode structure. Industry, for most applications, tends to prefer TEM₀₀.

One significant argon laser feature is its coaxial design, which simplifies manufacturing and reduces cost. Many parts can be mass-produced on automated production equipment. Additionally, the coaxial design simplifies mounting of the laser: It can be mounted in any radial orientation, assuming the system does not require any specific beam polarization orientation. Mirror alignment is also simplified, permitting adjustment over a wide temperature range. In fact, alignment adjustment can be achieved by three adjustment screws that position the mirror in its soft-metal support. This permits precise and permanent mirror alignment for optimum output power.

Operating life and power

Most of the electrical energy input to an argon laser is converted into

heat. To maintain mechanical stability and longevity, this heat must be dissipated through appropriate cooling and the use of properly selected materials. A typical 2–6mW argon laser will dissipate about 500–700W of thermal energy.

Conventional argon lasers have an operating life of around 5000 hours. A major reason for such a short life is that the BeO capillary begins to lose its insulating properties at typical high operating temperatures. Another effect of temperature on laser life is potential damage to various glass-to-metal and ceramic-to-glass seals. Metals with coefficients of thermal expansion close to, or equal to, those of glass are selected to reduce the material stress during cooling and heating. To maintain cleanliness and avoid contamination, mirror mounts in argon lasers are brazed to the electrodes at high temperatures for added protection.

Other design factors also play a part in gas purity. The hard-seal design of the contemporary laser tube permits degassing of the tube at higher temperatures (around 300°C) to obtain higher purity of final argon gases. With the higher temperatures it is easier to remove gases trapped in the tube walls through just a few purging cycles. However, to maintain the purity of the gases during actual laser operation — essential for long operating life — a getter is placed within the laser tube.

No discussion of argon laser life can be complete without at least a mention of operating current and output power. The argon laser can be operated in one of two modes: 1) constant output optical power with variable operating current, or 2) constant operating current with variable output power.

Figures 2a and 2b explain these two operating modes. In Figure 2a, laser output power is maintained

constant over the life of the laser. Note that, to achieve this, the laser current must be continuously increased. In Figure 2b, laser current remains constant throughout the laser life. Under this condition, the laser output power decreases with time.

Three major considerations form the basis for deciding whether to buy an OEM or an end-user laser:

- In-house design capability;
- In-field servicing; and
- Cost.

In-house design capability simply means that only companies that have the necessary knowhow and manufacturing facilities to incorporate it into their equipment should purchase an OEM argon laser.

In-field servicing refers to the fact that the cost of in-field replacement for an OEM laser is inherently lower. Indeed, in-field service involves bulb-like replacement of the laser tube rather than the entire laser module — assuming, of course, that the system is designed to permit easy replacement with little or no realignment.

Cost, the third consideration, should be evaluated from the viewpoint of *installed* cost; that is, the cost of an OEM laser cannot simply be compared to that of an end-user laser module. With an OEM laser, the equipment manufacturer has to take into account all the costs involved in providing the hardware necessary to incorporate the laser tube into the system. Obviously, an OEM laser also permits the designer a larger degree of freedom in designing the overall system. For instance, the overall package can be made considerably smaller than one built with a prepackaged end-user laser.

Mounting the argon laser

Because of the high operating temperatures and precision of an argon laser, extreme care must be ex-

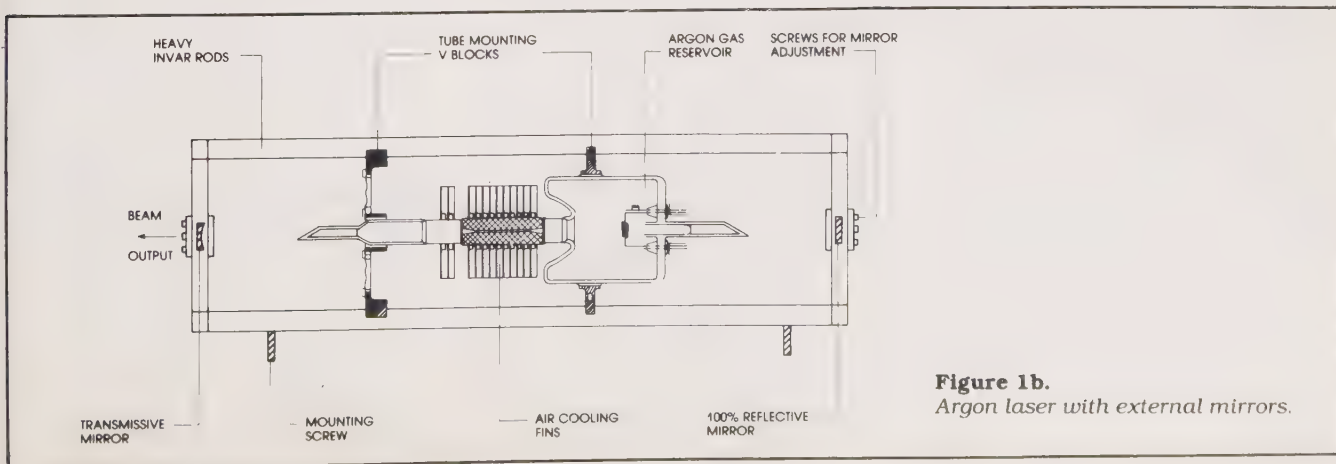


Figure 1b.
Argon laser with external mirrors.

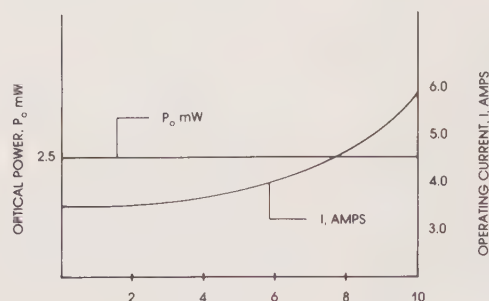


Figure 2a.
Operating mode with laser output power constant over the life of the laser.

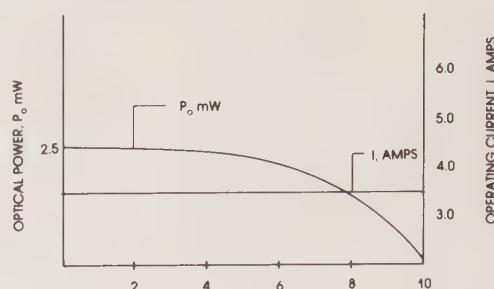


Figure 2b.
Operating mode with laser current constant throughout the life of the laser.

exercised in designing its mounting. An OEM unit comes with two mounting rings, one attached to the glass reservoir (cavity) and the other to the unit's output end (see photo).

Between the glass and the cavity ring there is a rubbery compound ("sealguard") to provide support and protect against shock and vibration over a wide temperature range. It also protects the laser against any shock encountered in shipping. The cavity ring, precisely machined, has a groove along its outer circumference for aligning the laser beam with the rest of the optical train.

The second mounting ring, on the laser tube near the beam exit, serves two major purposes: It acts as a spring to guard against shock, and it compensates for thermal expansion and contraction of the laser during normal temperature changes. For this purpose, the ring has a set of bellows that permit some axial motion and also act as shock and vibration absorbers.

Since, like the rings, the other laser parts are also manufactured with a high degree of precision, they allow the laser tube to be mounted with extremely close alignment. For instance, a typical Siemens argon laser tube can be mounted with the concentricity (diameter) tolerance of under 0.2mm and within 1 milliradian of angular alignment. It is this precision that permits field personnel to replace laser tubes pretty much like light bulbs — that is, without doing any realignment of optics. Such realignment would be costly under field conditions, requiring expensive test equipment and qualified personnel.

Since the rings described above provide the user with two concentric and highly precise mounting surfaces, the logical mounting arrangement is a precision-machined "V" block or an "L"-shaped bracket. Any

material can be used for such blocks, provided it can operate without distortion over a wide temperature range. This includes aluminum, steel, various grades of plastic and even wood.

Restraining the laser tube in the axial direction is the function of the groove in the cavity ring mentioned above. To restrain the tube within "V" blocks, a spring-loaded clamp is recommended, though care should be taken not to apply too much force to the laser. Excessive force may cause undue stresses within the tube, distorting the resonator alignment and causing a drop in power output.

Electrical connections are no problem, as argon laser tubes come pre-wired and connectorized. All that is required are mating sockets wired to the power supply.

Although there is no danger from either explosion or implosion of the laser tube (typical pressures in an argon laser are between 1 and 1.5 torr), the beryllium oxide material used in the capillary is considered toxic. For this reason, all used argon laser tubes should be returned to the manufacturer for proper detoxification and disposal.

Cooling the laser

An argon laser dissipates a large amount of heat, typically 500W, most of it through the BeO capillary. BeO is the choice material today because it is an excellent thermal conductor and an electrical insulator as long as it retains its original properties. However, excessive temperature will adversely affect its physical characteristics and thus directly the laser's life. Consequently a good cooling system is essential.

For adequate cooling, forced-air-cooled fins are mounted directly on the capillary with high-temperature solder. Made of copper, the fins are

designed to maintain an even temperature distribution around the capillary. This is extremely important to laser life. If the distribution is not uniform, hot spots occur, leading to rapid deterioration of the BeO capillary. In a typical argon laser cooling system, a temperature sensor mounted directly on the fins disconnects the laser automatically when the temperature of the laser reaches some predetermined unsafe value.

Another failsafe feature used with constant-power argon lasers is a current-limited power supply. One way to determine the end-of-life point of an argon laser is by establishing some current value for obtaining certain output power. For example, a new argon laser with a few operating hours may draw, say, 5A to produce 7mW of output power. Suppose we say that the laser end-of-life is defined as the point when the unit demands 7A of current to maintain the same 7mW of output. Then, by programming the power supply to switch off when its output current reaches that value, we have a system that will automatically notify us when the laser tube needs to be replaced. (In practice, the cutoff current value should be somewhat below the actual end-of-life figure, so that the user can order a replacement laser tube but continue operation at a higher current until the replacement arrives.)

All of this underscores the importance of the cooling system design. Regardless of the fan type used, it must deliver the air flow recommended by the laser manufacturer through the cooling fins. One must also make sure that all the air passes through the fins, and not over adjoining surfaces. Cooling the laser cavity or the laser tube near the mirror can actually cause resonator alignment distortion. Indeed, if some

of the cooling air flows over the cavity glass, "cold spots" may develop, causing glass distortion and adversely affecting the output power. In a constant-power system, a drop in power causes the system to demand more current, making a bad situation even worse and possibly resulting in a rapid "avalanche" laser failure.

Fortunately, one can direct the cooling air simply and inexpensively by adding a couple of baffles. Once an air flow is directed through a certain path, it will not deviate from it. Air leaving the fins must of course be allowed to do so freely, without any obstructions in its path. You must also make sure that cooling air enters the fan at room temperature.

Testing the argon laser

Testing the argon laser is similar to testing most other lasers. Four key parameters must be tested to ensure that a laser performs in accordance with its published specifications: output power, beam diameter, beam position and heater voltage.

● **Output power** measurements are extremely important, as the amount of power produced by a laser at a given operating current frequently determines its ability to perform in a system. In addition, accurate power measurements are needed to determine whether or not a given laser system is able to conform to requirements outlined by the National Center for Devices and Radiological Health.

Crucial to output power measurements is the selection of a suitable light detector. For best results, a detector sensitive to the argon wavelengths — 488 to 514nm — should be used. General-purpose optical power detectors may be less expensive and readily available, but a special meter produces better results.

● **Beam diameter** can be measured by several techniques. A good comparison of accepted and proven methods is contained in an article by LeRoy D. Dickson entitled, "Ronchi ruling method for measuring Gaussian beam diameter" (*Optical Engineering*, Jan.-Feb. 1979, p. 70). It compares four methods: scanning pinhole, knife edge, variable-width scanning slit, and Ronchi ruling. The Ronchi ruling method appears

to produce the best results in measurement accuracy and the amount of information it provides on beam parameters. In addition, it yields beam ellipticity and spatial noise.

● **Beam position** determines the alignment of the beam relative to the laser mounting surface. First, check concentricity by observing the spot produced by the beam near the laser output mirror. Next, to measure the angular alignment, rotate the laser in a precision "V" block and record the circular path produced by the beam at some distance. You can then determine whether or not the amount of misalignment is tolerable for the system in question. The radius of this circle, representing the alignment error, should be less than that specified. An "ideal" laser would produce a spot equal to the beam diameter, i.e., a "circle" with zero radius.

● **Heater voltage** is tested by a standard method. The power supply is turned on and, after about 10 seconds, the heater voltage is measured at the heater terminals of the laser tube to eliminate measurement errors that may be caused by lead resistance.

Selecting the power supply

For best results, power supplies for argon systems are custom-designed to match the laser used in the system — to ensure reliable system operation, long life, and low optical ripple. Some of the more important power-supply characteristics include:

1. Firing voltage — high-voltage pulse;
2. Heater voltage and current;
3. Operating voltage;
4. Failsafe provisions (i.e., an excessive cooling-fin temperature should cut off the power supply);
5. Two operating modes: Constant current (output power will gradually diminish as the laser tube ages) and variable current (for constant optical power output);
6. Proper operating sequence: i.e., in a typical application, as soon as the power supply is turned on, the two fans (one in the power supply, the other used to cool the laser-tube fins) must be turned on immediately. Subsequently the power supply must develop various operational outputs.

It should be noted that if the laser is to operate in a constant-power mode, the power supply must have a special feedback loop. Usually this is done by tapping a small portion of the optical laser output, converting it into an electrical signal, and then feeding the signal (after proper amplification) into a suitable power-supply current controller. Reputable argon laser makers provide power supplies designed to work with their lasers.

Argon laser applications

One application well suited to the argon laser is reprographics, where a laser scanner is used to expose film for multicolor offset printing. All color components of the object are exposed simultaneously with high precision by a split laser beam and then developed in a single-step operation. The time and cost savings in reprographics made possible by the blue beam of the argon laser result from reduced material costs through use of less expensive line film that is insensitive to red, and faster and simpler development, since line film can be processed in the normal red light of a darkroom.

Another growing application area is in various kinds of chemical and physical analyses where it is necessary to provide maximum light concentration in small areas and/or within narrow-band spectra. The argon laser's advantages here are several: Its blue beam penetrates liquid media much better than the red beam of the HeNe laser, and it also contrasts sharply with red media under investigation (e.g., in blood tests). Moreover, the short wavelength (488nm) and spectral purity of argon lasers are ideal for measuring sizes at molecular levels.

Still another application area extremely well served by the argon laser is in ophthalmology, where higher-power argon lasers now have a proven track record. They have become quite compact, thanks to the integrated mirror design, and are particularly well suited to diagnostic work, especially in raster scanners. The retina and other surface parts of the eye can be easily examined using photomultipliers and a screen.

Bhogi Patel
Siemens Components Inc.

Color Center Lasers: Comparative Features

	Crystal	FCL-10	FCL-20	FCL-110	FCL-120	FCL-130
Crystal	KCl:Na (#1)	$\geq 3\text{mW}$ @ $2.46\mu\text{m}$	$\geq 1\text{mW}$ @ $2.46\mu\text{m}$	-	-	-
Output	KCl:Li (#2)	$\geq 15\text{mW}$ @ $2.65\mu\text{m}$	$\geq 10\text{mW}$ @ $2.65\mu\text{m}$	-	-	-
Power*	RbCl:Li (#3)	$\geq 10\text{mW}$ @ $2.9\mu\text{m}$	$\geq 6\text{mW}$ @ $2.9\mu\text{m}$	-	-	-
	KCl:Ti (#4)	-	-	$\geq 100\text{mW}$ @ $1.51\mu\text{m}$	$\geq 100\text{mW}$ @ $1.51\mu\text{m}$	$\geq 100\text{mW}$ @ $1.51\mu\text{m}$ 20-30 psec pulses
Pump	KCl:Na (#1)	3W Ar 488/514nm	3W Ar 488/514nm	-	-	-
Laser	KCl:Li (#2)	1W Kr, 647nm	1W Kr, 647nm	-	-	-
Power	RbCl:Li (#3)	1W Kr 647/676nm	1W Kr 647/676nm	-	-	-
	KCl:Ti (#4)	-	-	2W $1.06\mu\text{m}$ YAG	2W $1.06\mu\text{m}$ YAG	2W $1.06\mu\text{m}$ YAG mode-locked
Crystal	KCl:Na (#1)	2.20 - $2.55\mu\text{m}$	2.20 - $2.50\mu\text{m}$	-	-	-
Tuning	KCl:Li (#2)	2.45 - $2.80\mu\text{m}$	2.50 - $2.80\mu\text{m}$	-	-	-
Range*	RbCl:Li (#3)	2.70 - $3.30\mu\text{m}$	2.70 - $3.30\mu\text{m}$	-	-	-
	KCl:Ti (#4)	-	-	1.43 - $1.58\mu\text{m}$	1.43 - $1.58\mu\text{m}$	1.45 - $1.56\mu\text{m}$
Typical	KCl:Na (#1)	1W/4W	1W/4W	-	-	-
Pump Power:	KCl:Li (#2)	0.1W/2W	0.1W/2W	-	-	-
Threshold**/	RbCl:Li (#3)	0.1W/1W	0.1W/1W	-	-	-
Maximum	KCl:Ti (#4)	-	-	0.1W/3W	0.1W/3W	0.1W/3W
Mode Structure and Typical Line Width***		Two modes, ~ 1 MHz line width 1.5GHz apart	Single mode, ~ 1 MHz line width	Two modes, ~ 1 MHz line width 1.5GHz apart	Single mode, ~ 1 MHz line width	~ 20 psec pulses @ $1.51\mu\text{m}$ $\sim 20\text{GHz}$ bandwidth 82MHz rep rate (optionally 100MHz)
Mode Spacing		275 MHz	295 MHz	275 MHz	295 MHz	-
Tuning		Grating	Grating, PZT Intracavity Etalon, PZT Cavity Mirror	Grating	Grating, PZT Intracavity Etalon, PZT Cavity Mirror	Birefringent Tuner, PZT Cavity Mirror
Pump Laser Polarization		Vertical	Vertical	Circular	Circular	Horizontal
Output		Horizontal	Horizontal	Horizontal	Horizontal	Horizontal

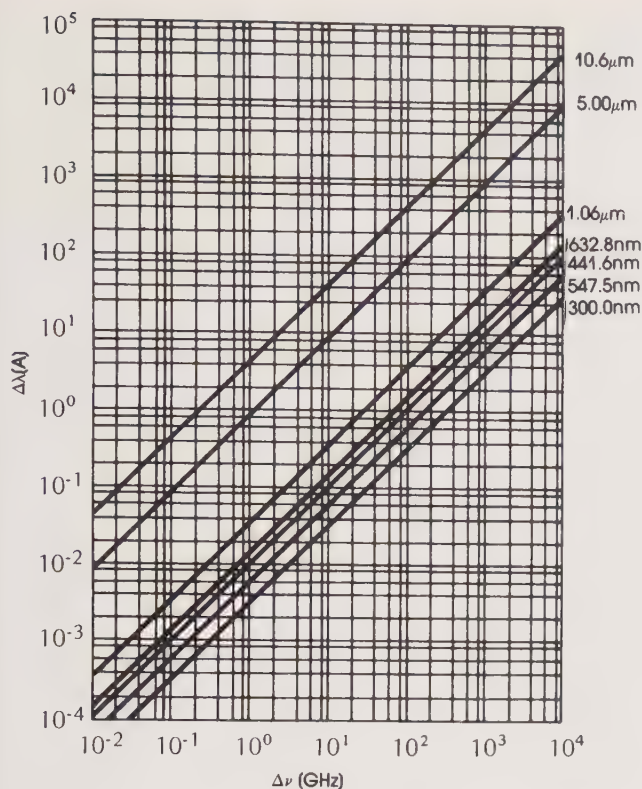
* Crystal output and tuning range assume specified pump laser conditions. Up to the maximum pump power higher output powers are generally possible.

** At pump wavelengths indicated under "Pump Laser Power".

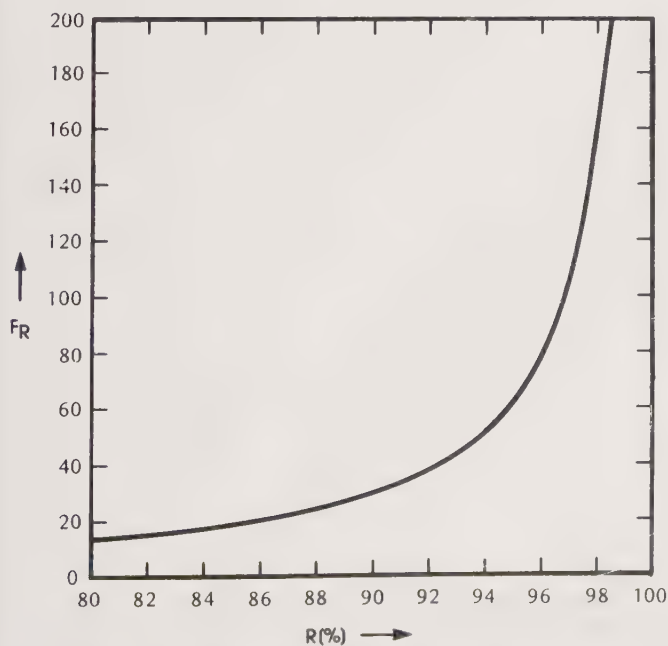
*** Line width depends on pump laser stability.

Note: Model numbers refer to Burleigh Instruments Inc. F-center lasers, but can be taken as indicative of which crystals are appropriate for an application and what accessory laser equipment might be required.

Fabry-Perot Interferometers



FREQUENCY-TO-WAVELENGTH CONVERSION



REFLECTIVITY FINESSE VS. REFLECTIVITY

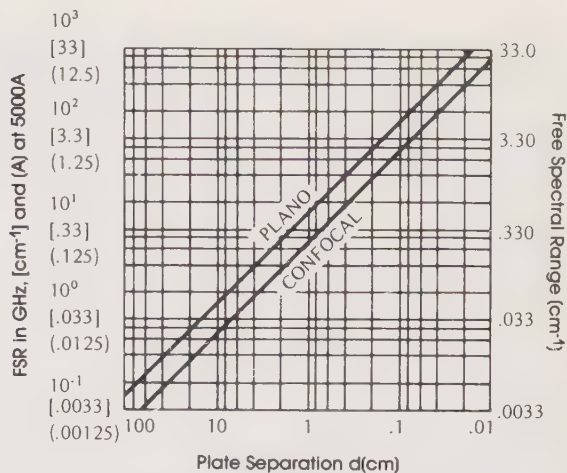
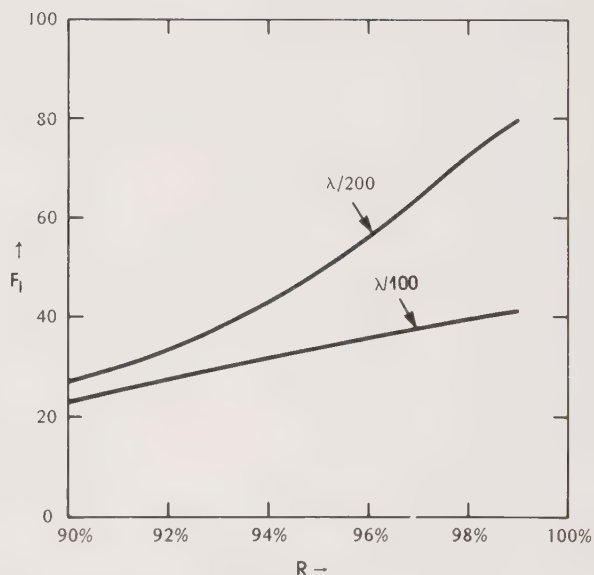


PLATE SEPARATION VS. FREE SPECTRAL RANGE (FSR)



NET FINESSE VS. REFLECTIVITY AS A FUNCTION OF PLATE FLATNESS

(assuming pinhole finesse = $1.5 \times$ plate flatness finesse)

The plots show theoretical net instrumental finesse (F_I) for $\lambda/100$ and $\lambda/200$ plates with a spherical error assuming the pinhole finesse is $1.5 \times$ the plate flatness finesse. To simplify the calculation diffractive finesse is not included.

Reflective Finesse (F_R): $F_R = \frac{\pi(R)^{1/2}}{1-R}$

Flatness or Figure Finesse: $F_F = M/2$ for λ/M plates

Fabry-Perot Selection Chart

Model	FREE SPECTRAL RANGE		Plate Spacing	Scan Range	Continuous Mirror Spacing	PZT Tuning	Max Aperture
	Frequency	Wavenumbers					
RC110	1GHz—50,000GHz	.033—1666.6cm ⁻¹	0—150mm	1.25μm	YES	YES	50mm
RC110IR	1GHz—50,000GHz	.033—1666.6cm ⁻¹	0—150mm	6.00μm	YES	YES	50mm
RC140	1GHz—50,000GHz	.033—1666.6cm ⁻¹	0—150mm	1.25μm	YES	YES	50mm
RC140IR	1GHz—50,000GHz	.033—1666.6cm ⁻¹	0—150mm	6.00μm	YES	YES	50mm
RC150*	15GHz—50,000GHz	0.5—1666.6cm ⁻¹	0—55mm	1.25μm	YES	YES	50mm
RC150IR*	15GHz—50,000GHz	0.5—1666.6cm ⁻¹	0—55mm	6.00μm	YES	YES	50mm
RC170	1.36GHz—50,000GHz	.045—1666.6cm ⁻¹	0—110mm	1.25μm	YES	YES	70mm
RC170IR	1.36GHz—50,000GHz	.045—1666.6cm ⁻¹	0—110mm	6.00μm	YES	YES	70mm
CFT25	3GHz	.1cm ⁻¹	2.5cm	1.00μm	YES	YES	10mm
CFT25IR	3GHz	.1cm ⁻¹	2.5cm	3.00μm	YES	YES	10mm
CFT100	750MHz	0.25cm ⁻¹	10.0cm	1.00μm	YES	YES	10mm
CFT100IR	750MHz	0.25cm ⁻¹	10.0cm	3.00μm	YES	YES	10mm
CFT500	150MHz	.005cm ⁻¹	50.0cm	1.00μm	YES	YES	10mm
CFT500IR	150MHz	.005cm ⁻¹	50.0cm	3.00μm	YES	YES	10mm
TL15**	15GHz—1500GHz	0.5—50cm ⁻¹	0.1mm—10mm	2.00μm	NO	YES	12mm
TL15IR**	15GHz—1500GHz	0.5—50cm ⁻¹	0.1mm—10mm	6.00μm	NO	YES	12mm
TL38**	15GHz—1500GHz	0.5—50cm ⁻¹	0.1mm—10mm	2.00μm	NO	YES	32mm
TL38IR**	15GHz—1500GHz	0.5—50cm ⁻¹	0.1mm—10mm	6.00μm	NO	YES	32mm
VS25	15GHz—1500GHz	0.5—50cm ⁻¹	0—10mm	N/A	YES	NO	20mm
VS25M	15GHz—1500GHz	0.5—50cm ⁻¹	0—10mm	N/A	YES	NO	20mm
SE—1	410.9GHz	13.7cm ⁻¹	0.25mm	N/A	NO	NO	20mm
SE—2	205.5GHz	6.85cm ⁻¹	0.50mm	N/A	NO	NO	20mm
SE—3	102.8GHz	3.4cm ⁻¹	1.0mm	N/A	NO	NO	20mm
SE—4	41.1GHz	1.37cm ⁻¹	2.5mm	N/A	NO	NO	20mm
SE—5	20.6GHz	.605cm ⁻¹	5.0mm	N/A	NO	NO	20mm
SE—6	10.3GHz	.34cm ⁻¹	10.0mm	N/A	NO	NO	20mm
FG—1	30,000GHz	1000cm ⁻¹	5.0μm	N/A	NO	NO	20mm
FG—2	6000GHz	200cm ⁻¹	25.0μm	N/A	NO	NO	20mm
FG—3	1500GHz	50cm ⁻¹	100μm	N/A	NO	NO	20mm
FG—4	600GHz	20cm ⁻¹	250μm	N/A	NO	NO	20mm
FG—5	150GHz	5cm ⁻¹	1.0mm	N/A	NO	NO	20mm
FG—6	60GHz	2cm ⁻¹	2.5mm	N/A	NO	NO	20mm
FG—7	15GHz	0.5cm ⁻¹	10.0mm	N/A	NO	NO	20mm

*With spacers 2.7GHz or 0.09cm⁻¹ (D—55mm)

**Defined with spacers of .1mm, .2mm, .5mm, 1mm, 2mm, 5mm, 10mm

Note: Though the model numbers above refer to Burleigh Instruments Inc. equipment, the information can be read as the relationship of the range of free spectral coverage to that of plate spacing. For additional information, Burleigh will supply a free copy of its "Tech Memo on Fabry-Perot Interferometry" on request.

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Cleaning and Handling of Optical Components

Precautions

Do not place a lens or prism on any surface unless it is protected with lens tissue or equivalent.

Never touch a polished optical surface with bare fingers.

All reticles should be handled only by their ground edges, and care must be taken that optically polished faces do not become marred.

Stoppers should be kept in acetone bottles at all times when not in use.

Cleaning swabs should not be dipped into the cleaning bottles (pour a small amount of solvent into a separate dish) or be redipped in the cleaning solution after use but should be discarded. Clean brushes in a mixture of alcohol and acetone and roll dry by spinning the handles or tapping.

Unmounted optics

Each polished surface must be cleaned separately. Removal of loose dirt, lint or both can be accomplished by brushing lightly with an optical brush prior to placing the optic on a clean and protected stable surface.

Employing a wiping cloth or swab liberally wetted with cleaning solution (alcohol, acetone or Orvus), the polished surface should be swabbed with a light pressure in a circular motion, starting at the center and gradually increasing the radius until the entire polished area has been cleaned. When the edge of the element has been reached, the swab should be gently slid past the edge to remove the accumulated lint. The foregoing operation must be repeated until no trace of dirt, lint, smears or other contamination is perceptible when observed with the aid of an eye loupe.

During the cleaning operation, unassembled optics should be held by the bevel or unpolished surface(s) in a suitable fixture or by hand (protected with lens tissue or equivalent) so as to avoid scratching, smearing or contamination.

Swabs and wiping cloths showing signs of contamination should be discarded and new ones employed as required, until the surface is satisfactorily cleaned. As the optical element becomes clean, the swab or wiping cloth has a tendency to drag,

indicating that the cleaning process is satisfactory. Store clean optics under a bell jar or in plastic trays fitted with transparent covers in order to eliminate unnecessary handling and prevent the elements from becoming recontaminated.

Reticles

The cleaning procedures outlined above do not apply to reticles, where the surface is more delicate due to the manufacturing process. To remove all possible contaminating material, reticles should be cleaned with a small jet of clean dry air or should be brushed with a clean optical brush. If oil, scum or finger marks remain on the surface and further cleaning is necessary, a soft cotton swab dampened with acetone should be employed.

Coated optics

Coated optics can be divided into two categories: hard-coated and cold-coated. The hard-coated surface can stand a fair amount of abuse before the coating film is destroyed. Cold-coated surfaces are subject to fast breakdown, even when cleaned with great care.

The cold-coated method is used only when the optical surface cannot withstand the heat of the hard-coated process or if the optics must be coated while still in their mount or container. In this case, the cleaning process must be limited to brushing the surface or wiping with tissue (damp or dry) with as little pressure as possible. As long as fifty percent or more of the coating remains intact, it will still serve its purpose to a great extent.

Where multilayer coatings are involved, use special handling techniques, following the coating vendor's instructions.

Mounted optics

In cleaning mounted lenses, alcohol or acetone should be used. Elements having considerable surface contamination should first be freed of dust using a small rubber syringe or a vacuum source, then rinsed with clean running water. This will remove the bulk of the loose soil and should eliminate scratching of the optic. A mounted lens should never

be removed from its mounting for cleaning.

Use a cotton swab moistened with alcohol to clean around the edges of the mount and the lens. (Use caution if the element is cemented to the lens mount.) This will remove any sealing compound that may have extruded over the edge of the lens. Sealing compound or grease must be removed as it will dissolve and spread onto the face of the optic. With an orange-stick swab (prepared with folded lens paper) dipped in acetone, the lens can be cleaned with a rotary motion.

As the cleaning operation progresses, the lens paper will have a tendency to drag, indicating a clean lens. Employing several papers moistened with acetone, and with a rapid rotary motion, give the lens a final cleaning. Acetone will remove dirt that alcohol will not, and having a higher evaporation rate, will hold drying marks to a minimum.

Lint or fibrous material still remaining on the optic can be removed from the surface with an optical and/or vacuum brush. If, upon examination, soil or drying marks are detected, the entire operation should be repeated until the optic is satisfactorily clean. After cleaning, place the mounted optics under a bell jar or in plastic trays with transparent covers until time of installation.

Instruments

The cleaning of optical instruments is a tedious process. The methods described for the cleaning of optical elements are also employed here; in addition to cleaning and replacing the components, care must be taken to ensure that the tubing, cells, etc. of the instrument are kept free of dust and dirt.

One concern in cleaning an instrument is the necessity of having a clean reticle. The reticle is in the image plane and all optics are focused on it. This is critical where the instrument may be used under poor illumination with a reticle illuminating system. Under certain conditions a small speck of dirt or dust may be mistaken for a target or object (particularly in missile tracking) resulting in an erroneous reading or signal.

Optical Machining: Controlling the Variables

In the fabrication of optical or optically related materials and components, a well-designed machine tool should be able to control both the primary and secondary variables in Table 1.

The primary variables are determined by their interdependency, because without just one of the four, the other three would not have any effect at all in grinding, shaping or polishing.

Abrasive

On this list, the size and type of abrasive are in parentheses because, even though the abrasive is a primary variable, it is usually controlled by the optician, not the machine. There are exceptions, as when, during a highly automated polishing process, the dispensing of one concentration of abrasive is stopped after a stock-removal stage, the surface is automatically flushed with deionized water and then a second concentration of slurry is introduced to the polishing surface. This is actually more controlling the dispensing of the abrasive (secondary variable) than choosing the size and type of abrasive.

Time

As with the other primary variables on this list, the amount of time two materials work against each other has a determining effect upon the influence and degree of necessity of the other three, within limits, of course. If, in order to make a product economically, very little time can be devoted to fine-grind each part, a machine can be made to supply a larger abrasive, greater pressure, or an increase in speed, and in that manner increase stock-removal rates. Time has a way of showing up later when because of an increase in abrasive size, pressure, or speed in the fine-grinding state, polishing times become lengthened. A remedy for this problem will be discussed later.

Time can be controlled on the machine by reset timers built into the electrical/electronic circuitry so that the cycle time can be exactly duplicated, as in the case of high-speed fine grinding when dimensional tolerance is critical (i.e., lens center thickness), or when one operator is running several spindles each with differently shaped or sized parts or different types of materials that

require polishing cycles of various durations.

Dwell or spark-out timers on curve generators, edgers, and also milling machines are valuable to ensure that the cut surface has minimal ridges from the effect of the diamond wheel against the work — that is, tool pressure. This helps control dimensional tolerances, and also helps reduce surface and subsurface fractures that would otherwise show up later as pits in the surface of a polished element, thus requiring regrinding and polishing.

Speed

The proper speed at which an optical fabrication machine is operated is usually described in terms of revolutions per minute (RPM). RPM

3000 surface feet per minute (SFM), the wheel must turn at approximately 5700 RPM, and to achieve 5000 SFM, it must turn at approximately 9500 RPM. By contrast, a 20-inch-diameter wheel must turn only between 570 and 950 RPM to achieve the same surface-feet-per-minute speeds. Table 2 illustrates this principle: $SFM = RPM \times \text{wheel circumference in feet}$.

According to diamond specialists, the 3000-to-5000-SFM speed range provides optimum cutting or stock-removal rates on most materials. There are exceptions, and a degree of trial and error may be needed on very hard, brittle materials such as sapphire and ruby, and also the softer materials such as cadmium telluride or zinc sulphide. A properly designed machine will provide a variety of speeds in order to accommodate many types of materials being cut by a wide assortment of diamond-wheel sizes, either by incorporating a series of stepper pulleys or adjustable shieve pulleys, or by using direct-current-variable speed motors. If a great deal of torque is required, the variable-speed belt system works well. If a wider speed range is desired, or if very low speeds are needed, the DC variable-speed motor system might be more applicable.

Proper speed, as it relates to the polishing process, is based upon completely different criteria. It is imperative that the parts being polished "fit" the lap — that is, be in uniform close contact with the surface of the pad or the pitch surface at all points. Theoretically, the space between the part being polished and the polishing lap surface should be the same dimension as the abrasive particle less the distance the particle is imbedded into the lap.

If the space becomes greater, then the phenomenon known as hydroplaning occurs: that is, the part being polished actually leaves the lap surface, causing many problems, such as "rolled" edges. Thus machine speed should not exceed the SFM point where hydroplaning occurs. This also depends upon down pressure, lap size, part shape, lap material, abrasive type, and size and method of dispensing the abrasive.

Other problems can be caused by excessive speed such as fracturing due to excessive heat build-up and/or out-of-control movement. Usually,

**TABLE 1.
FABRICATION
VARIABLES**

PRIMARY VARIABLES

1. Abrasive (size and type)
2. Time
3. Speed
4. Pressure

SECONDARY VARIABLES

1. Slurry, abrasive or coolant dispensing
2. Cleanliness of the work area
3. Repeatability
4. Stability
5. Temperature control
6. Ease of operation
7. Required maintenance
8. Accessibility of spare parts and maintenance assistance
9. Operator safety

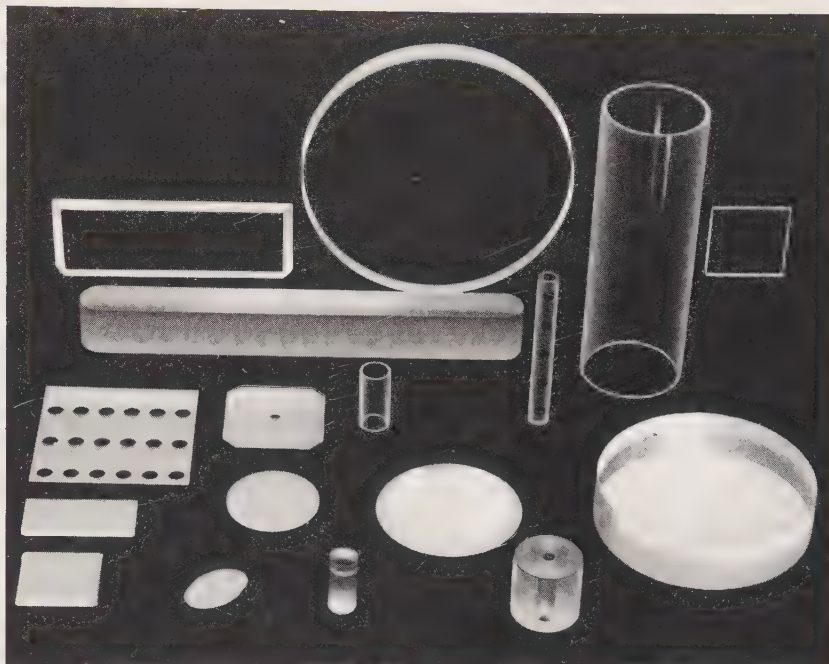
is a commonly used term, the concept being to count how many times in a given period (one minute) an object makes one complete revolution around a central axis. When applied to optical fabrication, or any similar shaping or cutting machine, the number of revolutions per minute is not the determining factor, but it is the key to determining the quantity of surface feet per minute that is being covered.

The rule of thumb for diamond-wheel speed on an edger or curve generator, for example, is approximately 3000 to 5000 surface feet per minute. This is much different from the wheel's RPM. In the case of a 2-inch-diameter wheel, to achieve

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if high-volume production is required, the parts are polished on a machine that runs at higher speeds. But if state-of-the-art flatnesses or extremely accurate radius work are required, a slower machine with a high torque rating is preferable.

Fine grinding with loose abrasive involves the same principles as shaping and polishing. Therefore, accurate control of machine speed is important in order to (1) develop a high ratio of surface feet per minute between lap and optic to enhance the abrading process, and (2) allow for a good "fit" between lap and optic. The required stock-removal rates are normally much higher in fine grinding, so higher machine speeds are common.

Pressure

Down pressure, another primary variable, is defined as the amount of down force in pounds divided by the square-inch surface area of the part that is being ground, shaped or polished.

Down force can be supplied on the machine by pneumatics, dead weight, springs or hydraulics, and is usually measured in pounds per square inch (psi). The amount of psi is strictly determined by the type of material being fabricated, its hardness, its structural strength, and the amount of stock that must be removed.

The machine must be built in such a way that this down pressure can be applied quickly, easily, and consistently to the work through mechanical means, or it must be built to accommodate a dead weight, as when the optician places a cast-iron or lead "donut" on the quill of a polisher. The required pounds-per-square-inch can range from less than one to up to ten or more.

Secondary variables

Secondary variables are provided and/or controlled by machinery in an effort to make the optician's job easier. They are not in the same "bare-essential" class as the four primary variables, but they help improve productivity and long-term profitability.

The abrasive can be dispensed by several methods, including drip-on systems and recirculating slurry feed systems, either in the fine grinding or polishing stage. Where fixed abrasive systems are used, such as during sawing, milling, generating, rounding, edging, and beveling, the machine must supply a coolant to the point of contact between the work surface and the diamond wheel in order to carry away the swarf or cut glass, clean the area between the individual diamond cutting points,

and help maintain a measure of temperature control through heat transfer from the material being abraded to the coolant (oil or water-based) as it flows over and past the cutting point.

Cleanliness of the work area is important, especially during polishing, and proper machine design dictates that the area close to and over the optic be free of grease, dust, metal flakes or powder, etc., and that no machine part near the work area be constructed in such a manner as to cause foreign material to contaminate the surface of the lap or the optic.

In order to accurately cut, mill, grind, polish or edge an optic, the machine must be built rigidly enough to absorb vibration and the tool-pressure stress associated with these processes. Every action has an equal and opposite reaction, so that as a machine produces pressure down onto the workpiece, it must also be able to withstand equal pressures in opposite directions. Otherwise repeatability and stability, essentials in material fabrication, are lost.

As tolerances for flatness, sphericity, asphericity, size, shape and function become more and more stringent, the control of heat and its effects on the lap and the optic are of greater and greater concern. A polishing machine able to maintain slurry temperature within a specified range such as $\pm 1^\circ\text{F}$ may be of considerable help to an optician attempting to polish state-of-the-art tolerances.

Ease of operation of the tools providing mechanical advantage will help make the optician more productive. In machine design these are

known as "creature comforts." The location of switches, handles, knobs and indicators, the work height of the machine, the accessibility to and ease of machine adjustments such as belt tensioning, speed changing or quill positioning are all important to keeping operator fatigue and strain within tolerances.

Along the same lines, required maintenance is of the utmost importance. A machine built to withstand the rigors of optical fabrication with limited required maintenance and down time must have sealed and heavily protected bearings; strong, stress-relieved castings; clean, heavy-duty weldments; oversized spindles and spindle supports; automatic lubrication systems wherever possible; easy-to-reach grease points; high-quality electronics, and more.

The accessibility of spare parts and maintenance assistance from the manufacturer becomes more important as time goes by. No machine lasts forever, but proper operator instruction, periodic maintenance, and the installation of recommended spare parts can extend the life of the machine dramatically.

The final consideration in machine design, but by no means the least important, is operator safety. Protective shields at critical points, polycarbonate lids and windows, moisture-proof switches, belt guards, spindle brakes, and large mushroom-style panic-stop switches help ensure against possible operator injury.

Use this checklist of essentials so that all primary and secondary variables are satisfied when purchasing a machine.

— Bob Roberts

R. Howard Strasbaugh Inc.

TABLE 2. RATIO OF RPM TO SFM

DIAMOND-WHEEL DIAMETER (inches)	RECOMMENDED RPM TO ACHIEVE	
	3000 SFM	5000 SFM
1.00	11,538	19,099
1.25	9174	15,291
1.50	7633	12,723
1.75	6550	10,917
2.00	5725	9542
2.50	4587	7645
3.00	3821	6369
3.50	3275	5459
4.00	2865	4776
4.50	2547	4244
5.00	2291	3820
6.00	1910	3183
7.00	1637	2728
8.00	1433	2388
10.00	1146	1910
12.00	955	1591
14.00	819	1364
16.00	716	1194
18.00	637	1061
20.00	573	955

Tools and Machinery: a Schematic Guide

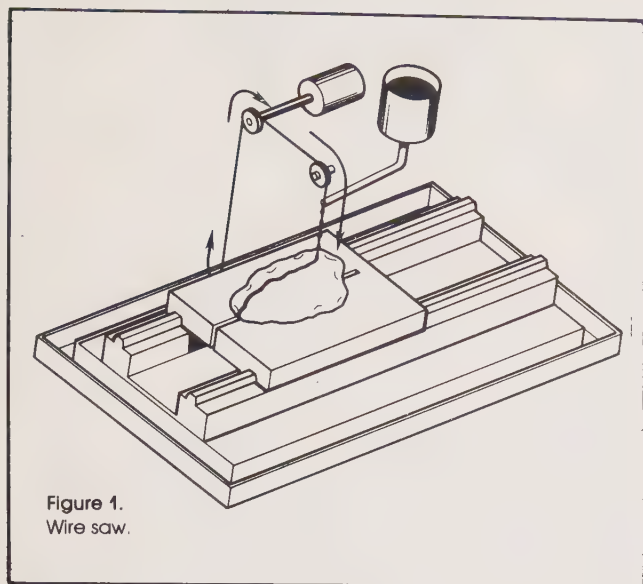


Figure 1.
Wire saw.

Figure 1.

In most optical shops, production begins with the surfacing of molded blanks, but production of the optical component has actually begun at the glass manufacturer's or the remolder's. Large pieces of cast, slab, sheet and extruded glass are sliced with wire saws like large bandsaws, with the glass slowly fed against the taut traveling wire. Conventionally, a stranded iron wire with an abrasive slurry feed is run into the cut, but with modern plating techniques, diamond-coated wires eliminate the loose abrasive and materially increase the speed of the operation. The wire saw is also used at the other end of the mass spectrum, with tiny wires and precise controls for particularly thin slicing of brittle and expensive materials.

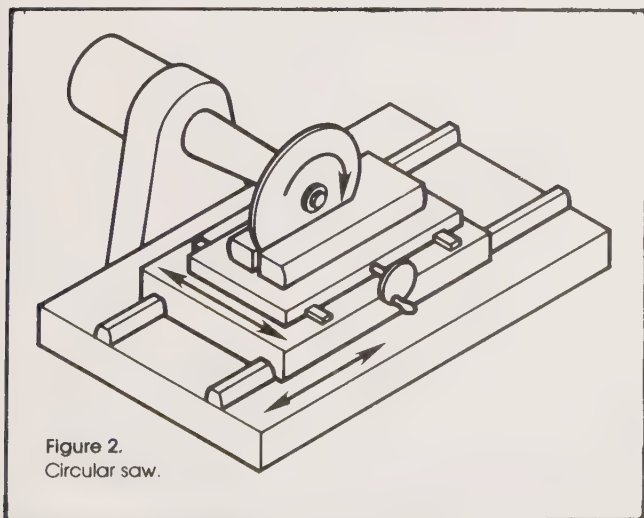


Figure 2.
Circular saw.

Figure 2.

The basic saw of the prototype shop is the conventional circular saw with a 250mm-to-500mm-diameter blade and metal-bonded diamond rim section. The saw assembly is cantilever-mounted, with the blade running in the vertical plane above

the work table. The work table feeds in the direction of the plane of the saw blade for the cut and adjusts at a right angle to the plane of the blade for offset, parallel slicing of the material.

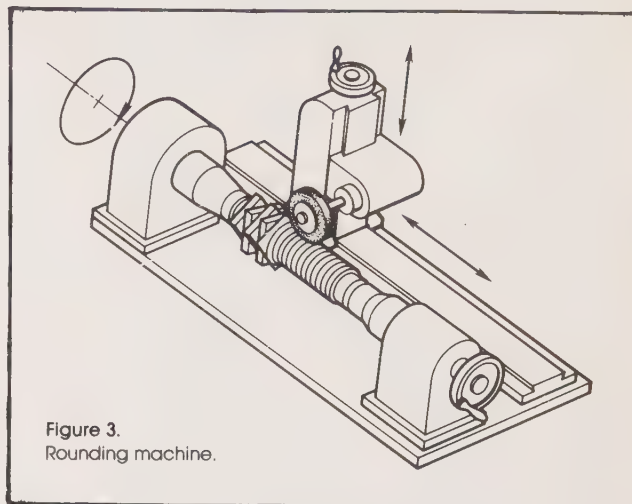


Figure 3.
Rounding machine.

Figure 3.

When glass for lenses has been reduced to squares (or octagons for larger pieces) and the appropriate thickness, it is rounded in typical OD grinders, mainly borrowed from the metalworking industry, or on later conversions carrying the grinding-wheel assembly on the crossfeed compound rounding machines.

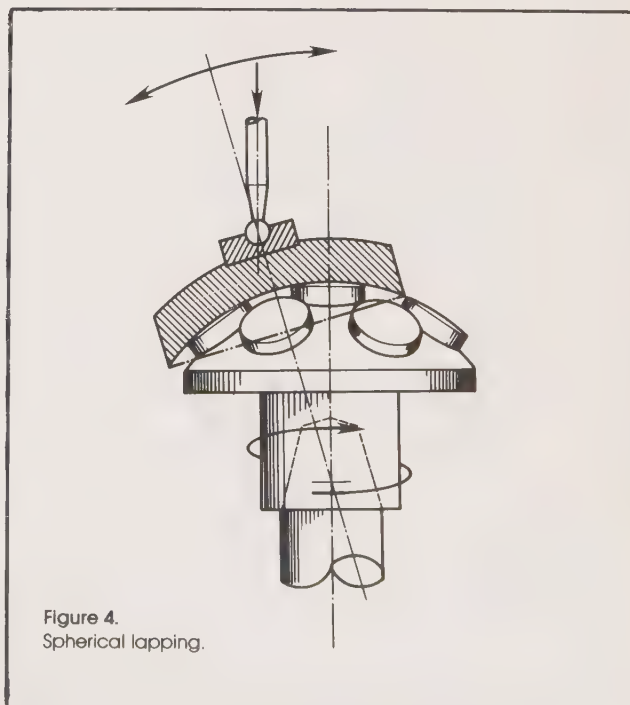


Figure 4.
Spherical lapping.

Figure 4.

In making simple components, the first surface is processed to completion, followed by the second,

and with prisms the third, and so on. One or more blanks are fastened to a plano plate or to a mushroom- or cup-shaped tool corresponding to the work radius of curvature to be produced. The number of pieces mounted on the tool is limited usually to a quantity that covers something less than a hemisphere — about a 150° solid angle in practice — or some convenient maximum tool diameter. The glass surfaces are lapped with a tool of mating radius and slurries of successive refinement. The abrasives (aluminum oxide, silicon carbide, garnet, etc.) rolling at the interface of glass and tool produce the grinding action.

In the schematic operational example, the mushroom-shaped tool (mounting convex lenses) is set on a vertically oriented rotating spindle and the cup-shaped lapping tool is set on top. A pin-center engaging the lap's socket-center imparts oscillation and applies working pressure. While the lap tends to rotate with the work, the displacement of the axes of the two elements produces relative motion over the entire interface. Adjustment of the pin stroke for different sweep lengths and positions produces changes in relative glass/tool wear and a consequent controlled drift to longer or shorter radii. This powerful tool for precise figure control is fundamental to all optical lapping processes.

Empirical wisdom says that the arc span of the lower (convex) rotating element and the upper (concave) oscillating element should have a relationship of about five to four; that the length of stroke should be approximately one-third of the tool's arc span; and that for a "neutral" action, maintaining a given radius, the stroke should run over center, one-third to one side and two-thirds to the other. Radius changes may be produced by shifting the sweep to a more centered setting for lengthened radii and vice versa.

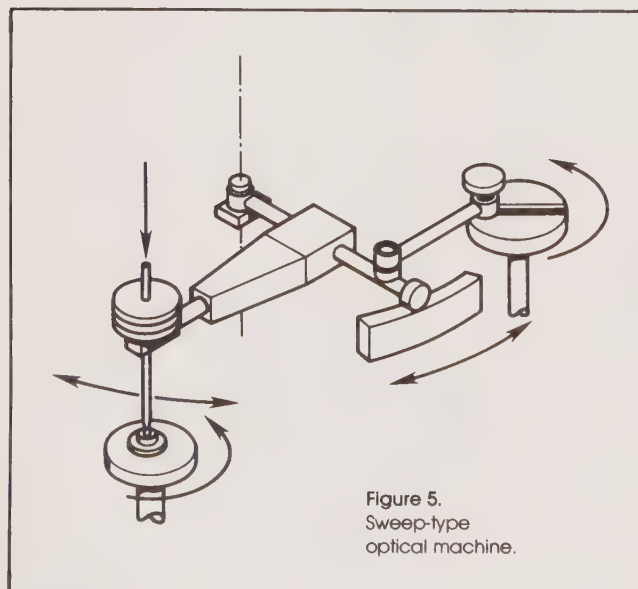


Figure 5.
Sweep-type
optical machine.

Figure 5.

The fundamental optical surfacing machine with a sweep-type pin-arm incorporates the driven vertical spindle and the adjustable oscillating pin-arm. While modern equipment incorporates variable-speed drives, pneumatic pin-arm pressure and operation, cycle timers, pumped slurry feeds, etc., the basic operating conventions still apply. Also, variations from the basic machine type abound, many for narrow-range application.

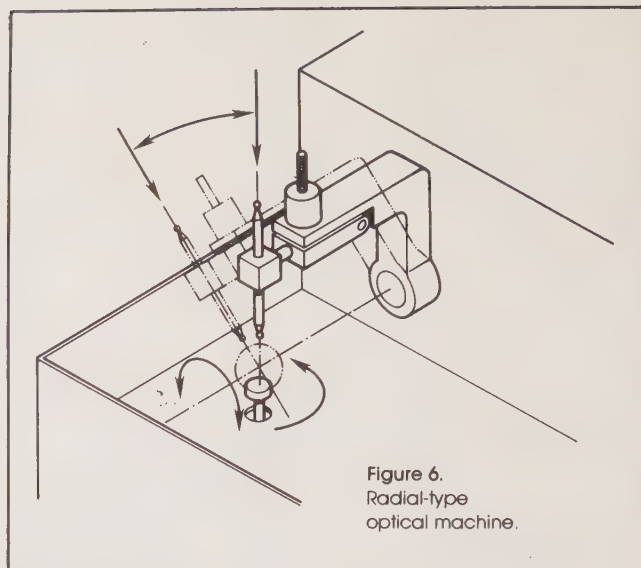


Figure 6.
Radial-type
optical machine.

Figure 6.

One special machine type for broader application is the radial pin-arm machine. It is constructed for lapping comparatively short-radius work with longer arc spans, from the 150° range to hyper-hemispheres. The oscillating pin-arm axis is at right angles to and intersects the vertical rotating-spindle axis. The point of intersection of the two axes determines the proper position of the radial center of the work. In this construction, the oscillating pin center operates through its entire swing at a normal attitude to the work surface, applying a constant radial pressure irrespective of its angular position and eliminating the mechanical "binding" constraints of the sweep-arm machine at extreme swings.

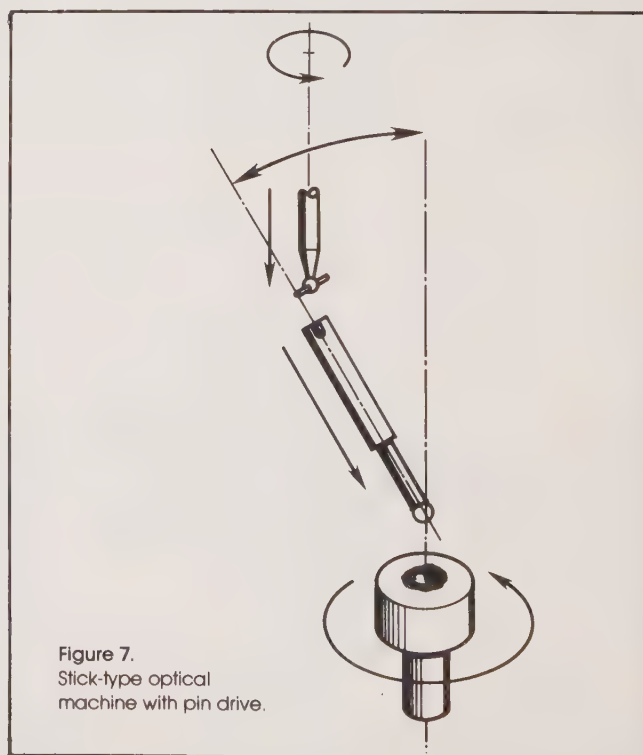


Figure 7.
Stick-type optical
machine with pin drive.

Figure 7.

The stick machine is a variation of the radial type, used principally in production of microscope objectives, cystoscope elements, etc. Contrary to the

convention of operating with the convex element on the rotating spindle, the concave lap may be mounted on the spindle and the convex work oscillated "upside down." But then the lens is mounted on a (dopp) stick of a length at least several times the lens radius to put the pin socket well away from the work center of oscillation. With particularly small lenses with diameters on the order of the pin-center's, there may be less drag at the lap interface than at the pin-center. It then becomes necessary to use a rotational pin drive.

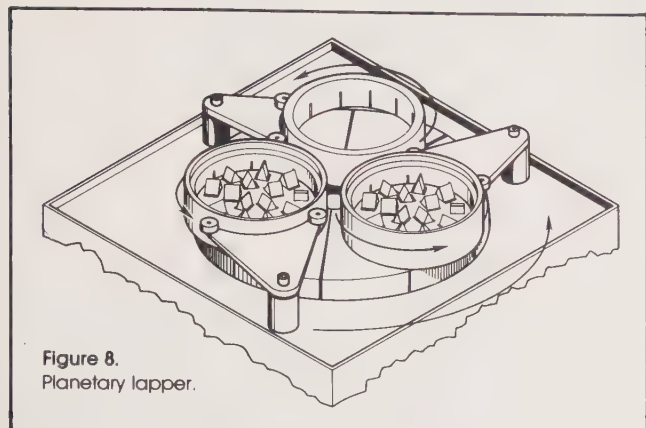


Figure 8.
Planetary lapper.

Figure 8. The planetary lapper incorporates a large annular lap on the rotating spindle with multiple and usually nonoscillating work stations. Because precise figure control of the lap and work surfaces can be hard to achieve with the disparity of working conditions across the lap and without oscillation, one work station is used for lap "conditioning." The conditioning lap (ring) tends to have greater effect on the primary lap's surface geometry than the aggregate tendency of the work to deform it. A particularly important feature of the planetary machine is its capability to accommodate unblocked, irregularly-shaped pieces laid loose or trapped in predicated cages.

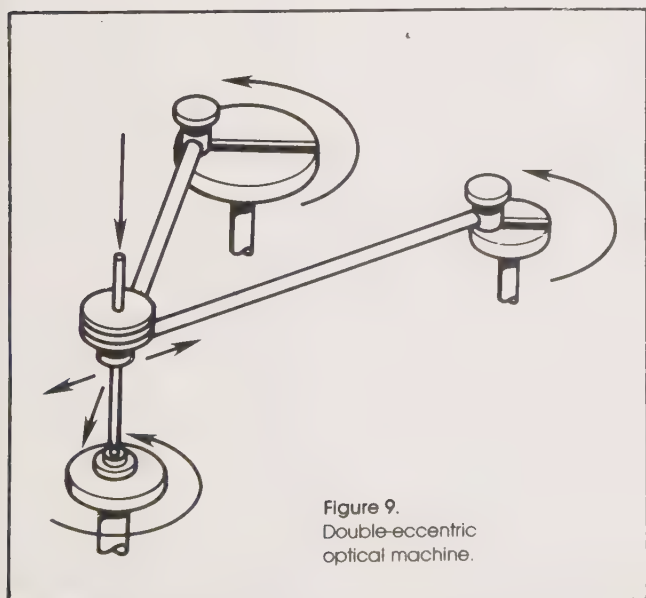


Figure 9.
Double-eccentric
optical machine.

Figures 9 and 10.

While basic lapping theory produces spherical shapes of high quality, the mutual interaction of lap and work is not truly linear from center to edge and does not achieve "perfect" spheres. Indeed, require-

ments may be for specific, nonspherical surfaces. In such circumstances, a capability for working-surface zones is required, and a lap significantly smaller than the diameter of the work may be employed. Also, a capability for blending or

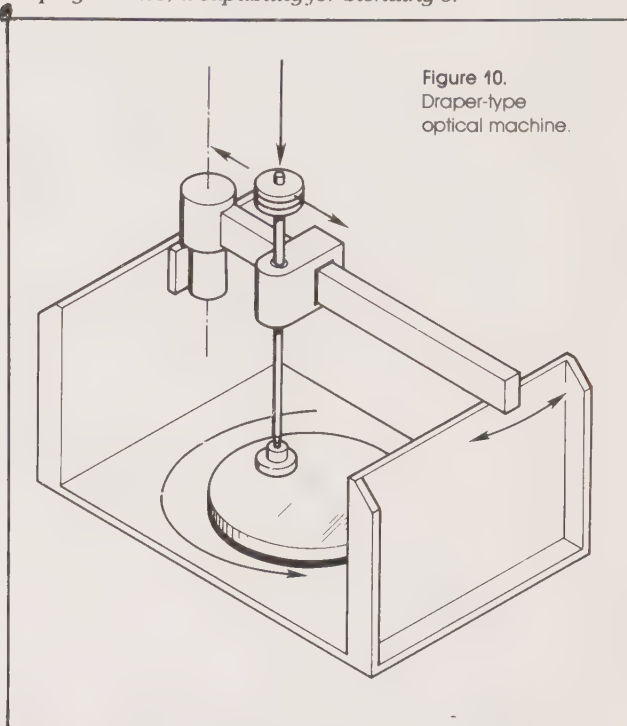


Figure 10.
Draper-type
optical machine.

vignetting the worked zone is necessary. The double eccentric (Figure 9) and Draper-type machines (Figure 10) incorporate compound sweep pin-arm drives, which provide for infinitely variable, "random" sweep limits.

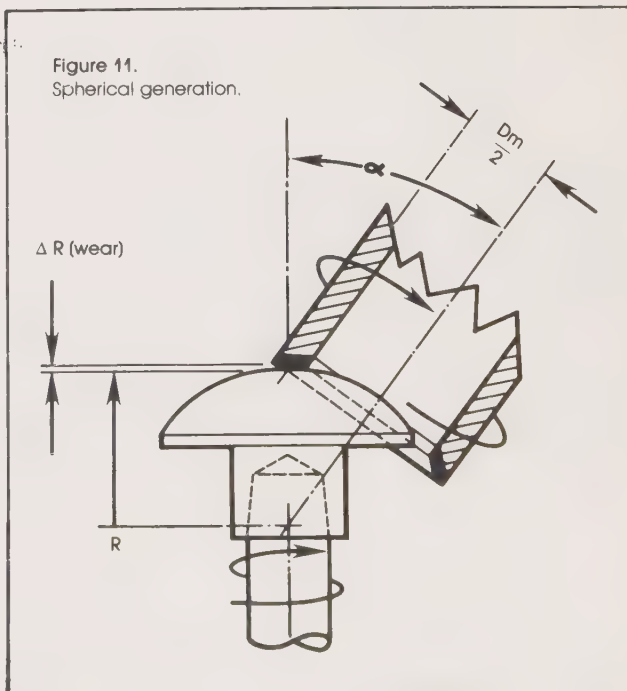


Figure 11.

The optical curve generator is essentially a special rotary-table milling machine incorporating a 45° tilt adjustment of the grinding spindle. Whereas, in lapping, one tool floats or follows the other, in

Lenses

generating, both the grinding tool and the glass tool turn on fixed axes.

Considering the circumstances of a ball-and-socket joint, either member can rotate independently, the axes can be at considerably divergent angles, and the only shapes that "work" are spherical. Then, considering an optical production example, the "ball" is reduced to a lens, and the "socket" is only the end of a cup-shaped grinding tool. In the actual machine, the lens rotates on its axis and is fed against the grinding tool. Practically, the grinding tool diameter and the inclination of its axis to the work axis must be such that the contact circle between the two components runs over the top dead-center of the work and down off the edge. The axes intersect at the work center. In the standard machine, at some selected position of the grinding tool head in its range of angular adjustment and lateral offset, any spherical shape, convex or concave from hemisphere to plano, is possible.

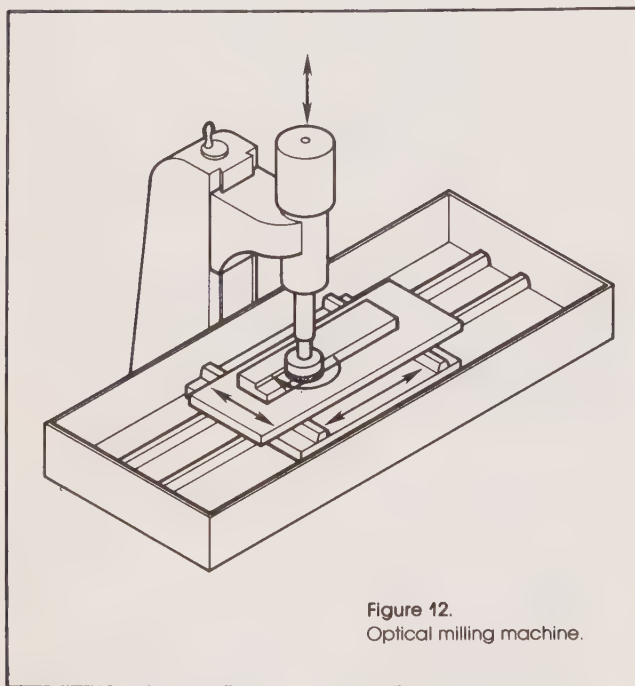


Figure 12.
Optical milling machine.

Figure 12.

The glass mill, with rectilinear feeds and adjustments of the work table instead of the curve generator's rotational work spindle, is used primarily in prism work, for rough surfacing, and for boring, coring, and trepanning operations.

Figure 13.

In the classical edger, the lens is mounted with wax to a cup-shaped adapter on a precise spindle so that the optical axis of the lens coincides with the spindle axis. A grinding wheel then eliminates the

eccentricity in reducing the oversize lens to a given diameter and bringing the cylinder edge and optical axis into coincidence.

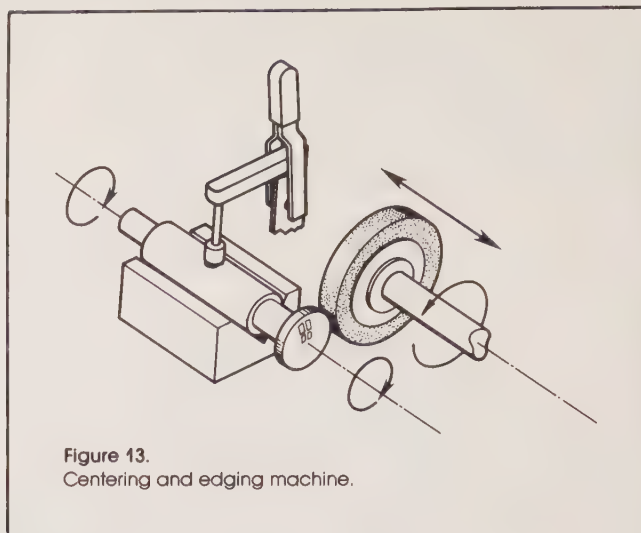


Figure 13.
Centering and edging machine.

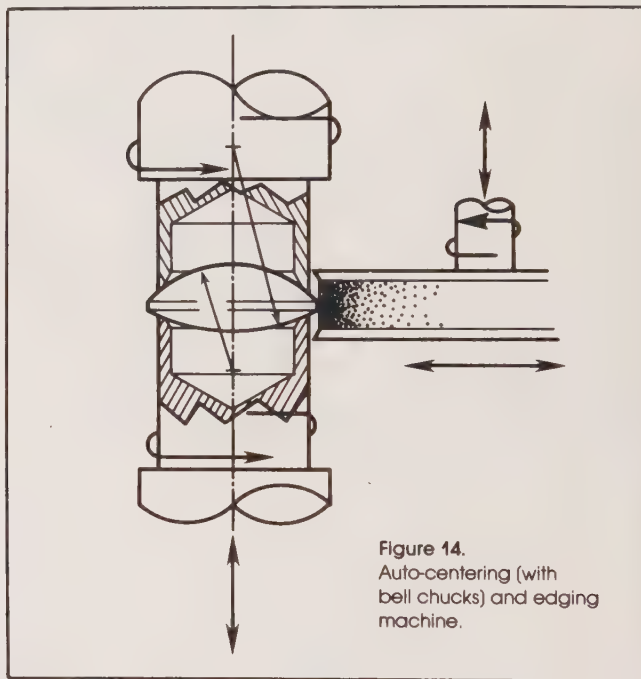
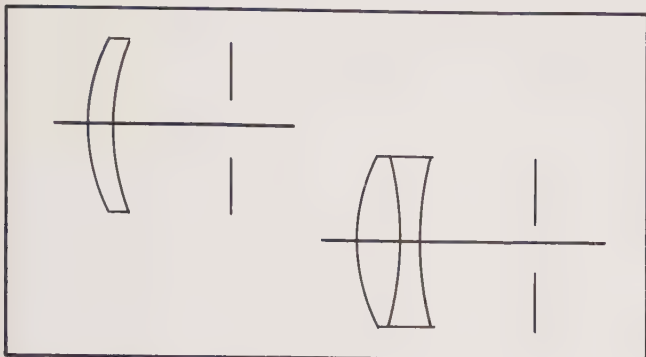


Figure 14.
Auto-centering (with
bell chucks) and edging
machine.

Figure 14.

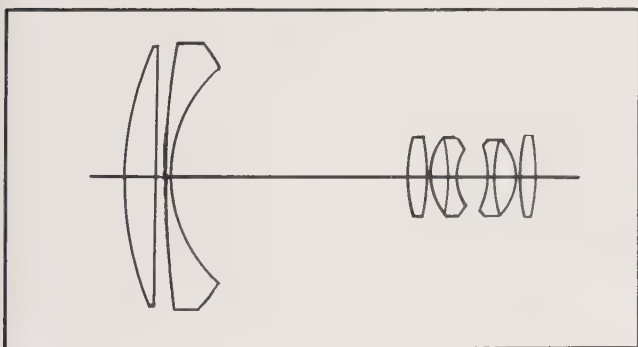
Modern machines utilize two opposed collinear spindles to clamp lenses between them, automatically centering the lens. These machines also incorporate a cycle feature to produce precise, centered bevels. Finally, laser collimation is added to assist operator centering adjustments when the power of the element is too weak for mechanical centering. —F.W. Clarke
Rogers & Clarke Mfg.

Photographic Objective Lenses: A Schematic Guide



Simple Meniscus Lens

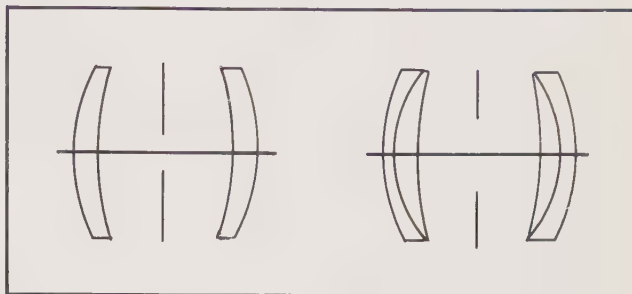
The Simple Meniscus lens is almost universally used in inexpensive cameras. To get an image of good quality it must be used with a separate aperture stop, reducing the aperture of the lens and the aberrations and their effects. The stop also selects the pencil of off-axis rays that passes through the lens; this controls astigmatism and eliminates coma. Spherical and chromatic aberrations and field curvature are totally uncorrected, but are rendered tolerable by the low speed—about $f/15$. Distortion is uncorrected. The stop may be before or behind the lens, although it is always on the concave side. If the meniscus lens is compounded, chromatic aberration can be corrected and spherical reduced slightly, but this is not an economical solution.



Retrofocus

The Retrofocus, or Reversed Telephoto lens, is usually composed of an ordinary objective with a negative component near its front focal point. Because of its relatively large back-focus and size, it is most useful for short-focal-length, wide-angle applications. In its early form the rear member was a standard objective, but modern versions tend to be designed as a unit and are difficult to classify.

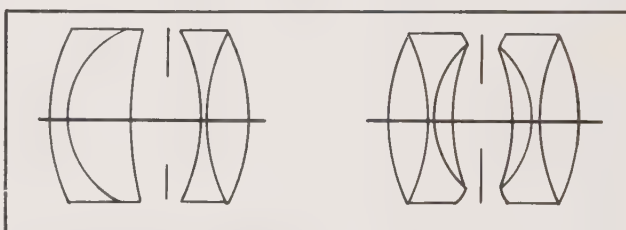
A new class of wide-angle lens has evolved from this form, as the bending of ray bundles outward by the negative member lends itself to this application. In a wide-angle configuration there is usually a fairly complex positive member closely enveloping the stop with symmetrically arranged negative elements on either side.



Double Meniscus System

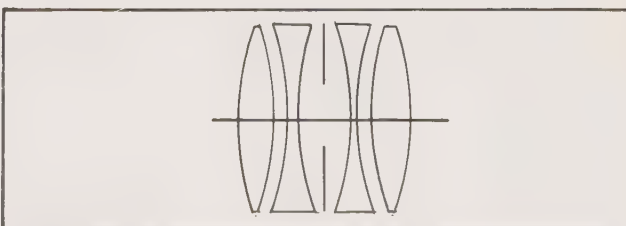
The arrangement of the two simple meniscus lenses on either side of the aperture stop is called a Periscopic lens. Symmetrical about the stop, it has greatly reduced coma, lateral color and distortion. Spherical aberration is slightly better than in the single meniscus, but axial color and field curvature are slightly worse.

If the two menisci are achromatized, the chromatic aberration is eliminated and the spherical is somewhat reduced. However, the remaining spherical aberration and the field curvature limit the lens to a speed of about $f/8$. Known as the Rapid Rectilinear, this was once a very popular lens for medium-priced cameras.



Meniscus Anastigmats

The first true anastigmats used a thick meniscus construction to achieve the wide separation of convex and concave surfaces necessary to flatten the field. Correction of chromatic and spherical aberration was accomplished by the cemented surfaces. Although limited to speeds of $f/8$ to $f/4.5$ by heavy residual spherical aberration, these anastigmats are still useful as moderately wide-angle lenses, and are capable of excellent definition when stopped a bit below their full aperture.

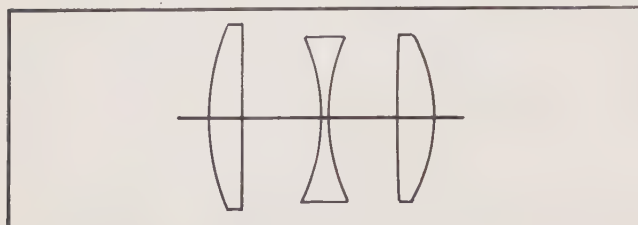


Dogmar/Aviar

Historically known as the Celor, this lens was derived from the Dagor, although it can be regarded as a

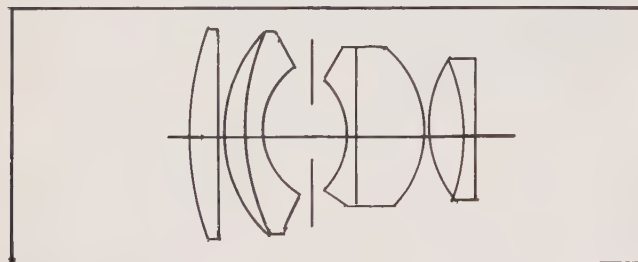
Lenses

triplet with a split flint element. It is an excellent general-purpose photographic lens and can be designed with a wider-than-normal field. This design form is also used extensively in high-quality commercial process lenses.



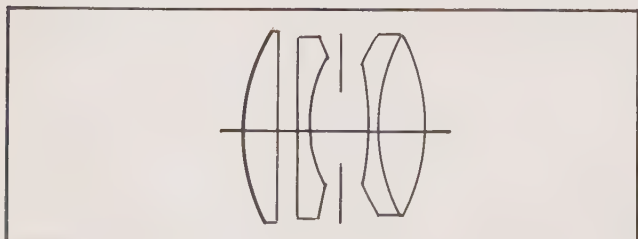
Cooke Triplet

The Cooke Triplet Anastigmat is the simplest lens in which all the primary aberrations may be corrected. Consisting of two positive crown elements on either side of, and spaced away from, a negative flint element, this lens gives the designer the necessary freedom (shapes, powers and spacings) to do a reasonably complete correction job. As a result it is a popular and economical choice for a wide range of applications. At $f/5.6$, compact triplets can cover fields up to 60° . At the other extreme, high-index crown glasses make speeds above $f/2$ feasible for short-focal-length, narrow-angle applications. The Cooke Triplet is probably the most widely used photographic lens, either in its original form or in one of its many derivatives.



Double Gauss

This is one of the most powerful design forms and is the basis of most high-speed (over $f/2$) camera lenses. Derived from the Gauss form of telescope objective, which consisted of a meniscus crown and a meniscus flint, both convex to the long conjugate, the Double Gauss retains the excellent spherochromatic correction of its ancestor. Perhaps the most serious defect in this design is oblique spherical aberration, which is usually kept in check by carefully vignetting the oblique pencils. Many modifications of this design exist; the outer crowns have been split and compounded and the doublets have been air-spaced and made into triplets.

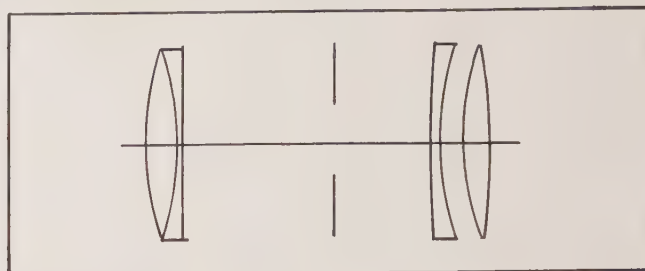


Tessar

Although it is externally very similar to the Cooke Triplet, the Tessar was actually derived from the Protar, a totally different form of lens. While its ap-

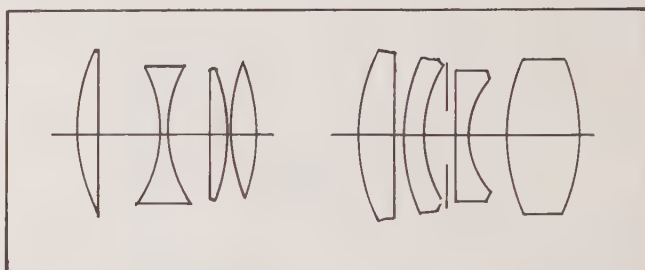
Photographic Objectives

plications, coverages and speeds are similar to those of the triplet anastigmat, the Tessar is a significantly better lens, usually showing somewhat better coverage, definition or versatility. Most good enlarging lenses and medium-speed "normal" camera lenses are of the Tessar type.



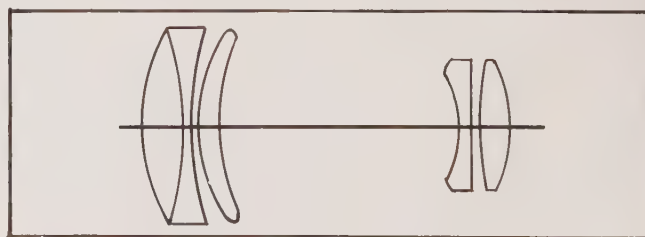
Petzval Lens

Because of its relatively high speed ($f/3$) and narrow field of good definition, the Petzval lens was originally used in 19th century portrait photography. In its modern form the order of the elements in the rear achromat is reversed and the elements are cemented together. Useful for motion picture projection, the lens has been increased in speed to about $f/1.6$, but angular coverage is limited by field curvature to about 10 degrees.



Split-Crown Triplets

These descendants of the Cooke Triplet were created by splitting one of the crown elements into two to reduce the aberrations. The improvement has primarily increased the speed of the lens. For example, with ordinary dense barium crown glass, the Cooke Triplet is limited to speeds of about $f/3.5$. With a split crown element the aperture is approximately doubled, although the field coverage is reduced.

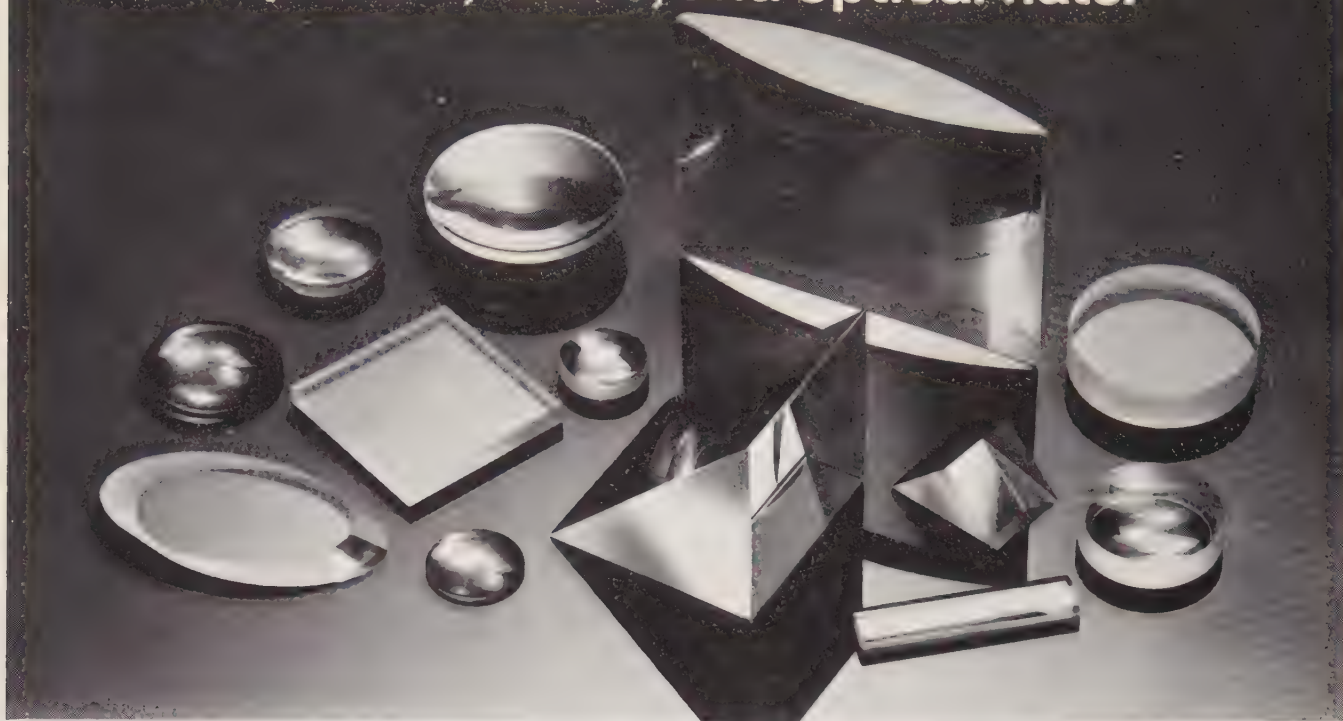


Telephoto

A Telephoto lens has a focal length that is longer than the distance from the front vertex of the lens to the focal plane. This is accomplished by using a positive front member widely separated from a negative rear member. Distortion is difficult to control because of the basic lack of symmetry, but the arrangement does tend to flatten the field. However, extreme telephoto ratios cause an overcorrection of the field curvature because of the strong negative member required.

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The USAF 1951 Resolving Power Target

The need to assign numerical tolerances to the performance of optical systems and photographic processes has resulted in the general acceptance of the present USAF 1951 resolving power target. The range of resolution is dependent upon the quality and function of the system or process being tested. Production of these targets is accomplished by many processes dependent upon tolerances and also upon durability requirements.

Military Standard 150A defines the basic pattern dimensions to be employed in the popular "Air Force" target. Briefly, an element consists of two target patterns of three lines each, at right angles to

each other. The width of a line is equal to the width of a space, and the line length is five times its width.

In the standard Air Force 1951 target, the change in pattern size is in a geometric progression based on the sixth root of 2. More simply stated, the number of lines per millimeter doubles with every sixth target element. These six elements are known as a group, and the group heading, such as -2, is the power of 2 to which the first element is raised to express the number of lines per millimeter in that element. In other words, two to the minus 2 power (2^{-2}) is 0.25 line per millimeter, two to the zero power (2^0) is one

line per millimeter, and so forth.

This is greatly simplified for the occasional user by reference to Table 1 below.

Contrast defined

Resolution targets are used both in negative (clear lines on an opaque background) and positive (opaque lines on a clear background) imagery. Contrast is a logarithmic function of the density difference (ΔD) between the line and the background.

For Types I and II lenses, as defined in Military Standard 150A dated 1959, negative targets are preferred. For Types IV, VI, VII, XII and XIII lenses, however, positive targets are preferred.

Contrast	ΔD^*	%Transmission	Contrast Ratio
High	2.0+	1.0	100:1
Medium	0.8 ± 0.05	16.0	6.3:1
Low	0.2 ± 0.05	63.0	1.6:1

*As per Mil. Std. 150A with change #1.

Table 1.
Number of Lines per Millimeter in USAF
Resolving Power Test Target 1951

Element No.	Group Number										
	-2	-1	0	1	2	3	4	5	6	7	
1	0.250	0.500	1.00	2.00	4.00	8.00	16.0	32.0	64.0	128.	
2	.280	.561	1.12	2.24	4.49	8.98	17.95	36.0	71.8	144.	
3	.315	.630	1.26	2.52	5.04	10.1	20.16	40.3	80.6	161.	
4	.353	.707	1.41	2.83	5.66	11.3	22.62	45.3	90.5	181.	
5	.397	.793	1.59	3.17	6.35	12.7	25.39	50.8	102.	203.	
6	.445	.891	1.78	3.56	7.13	14.3	28.51	57.0	114.	228.	

Image format — $\frac{1}{4}$ to 228 lines/mm target.

SOURCE: TELEDYNE GURLEY DIV.

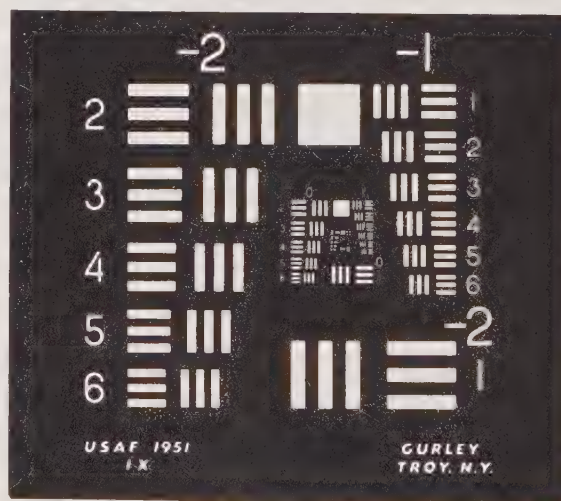
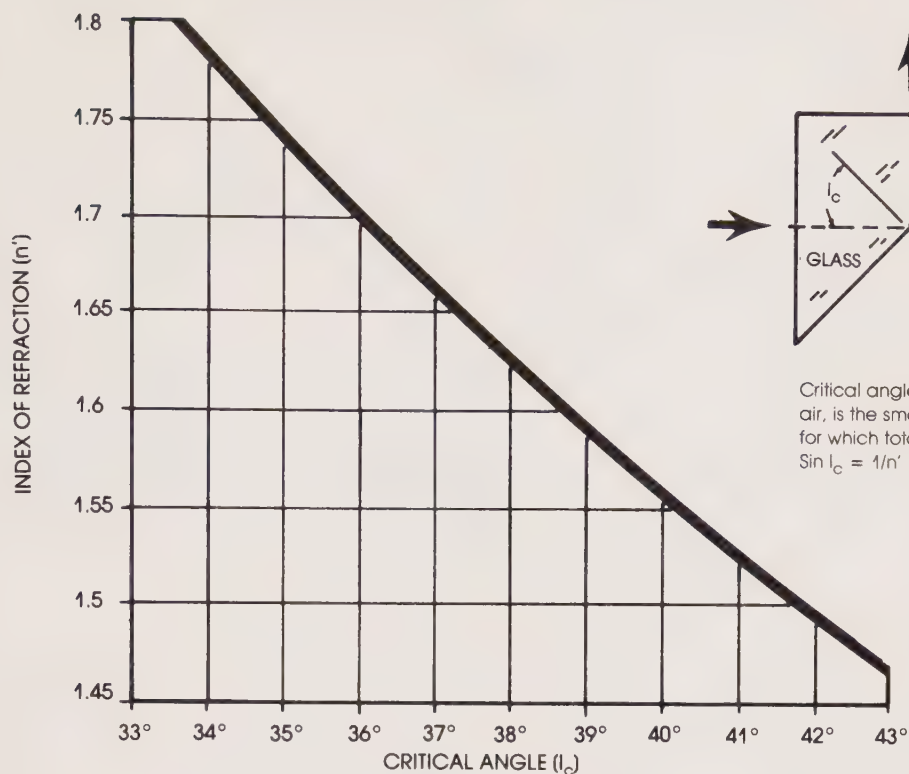
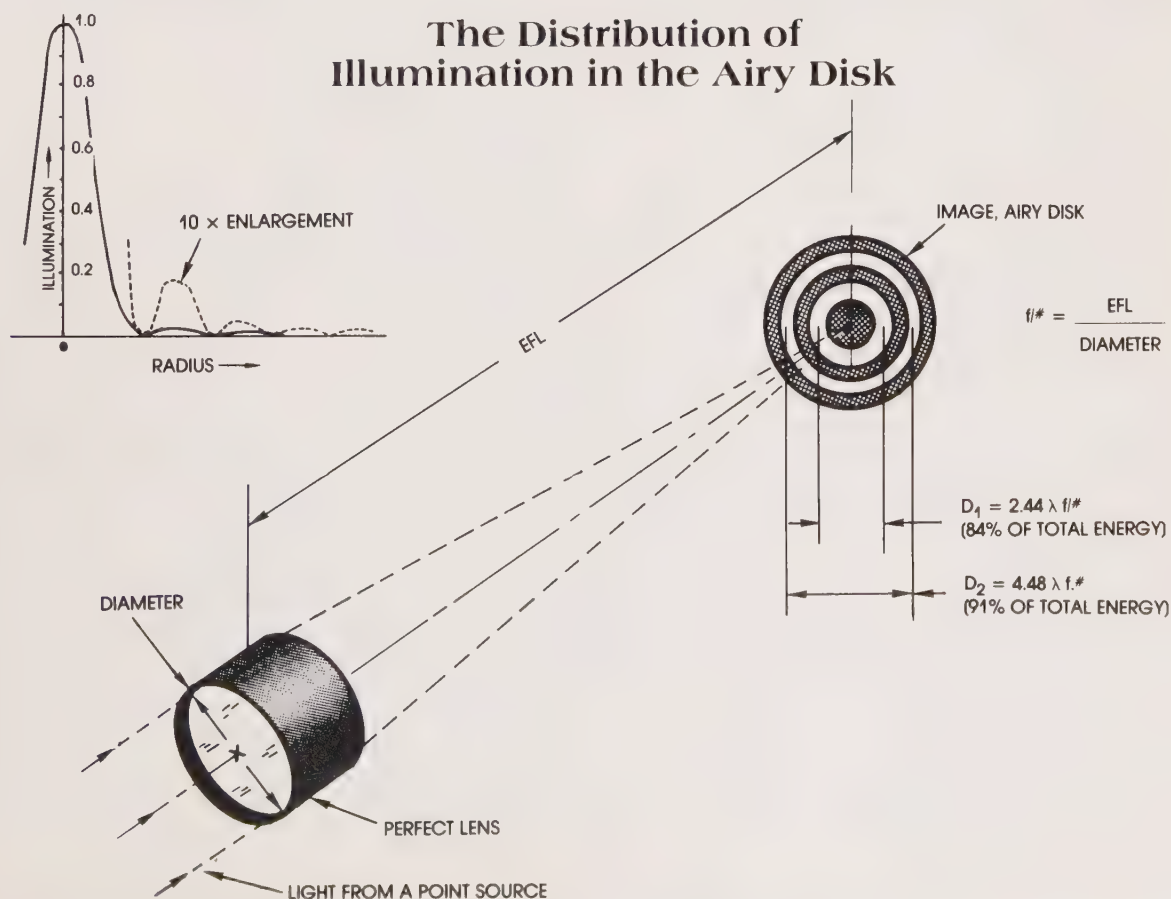


Image format — $\frac{1}{4}$ to 228 lines/mm target.

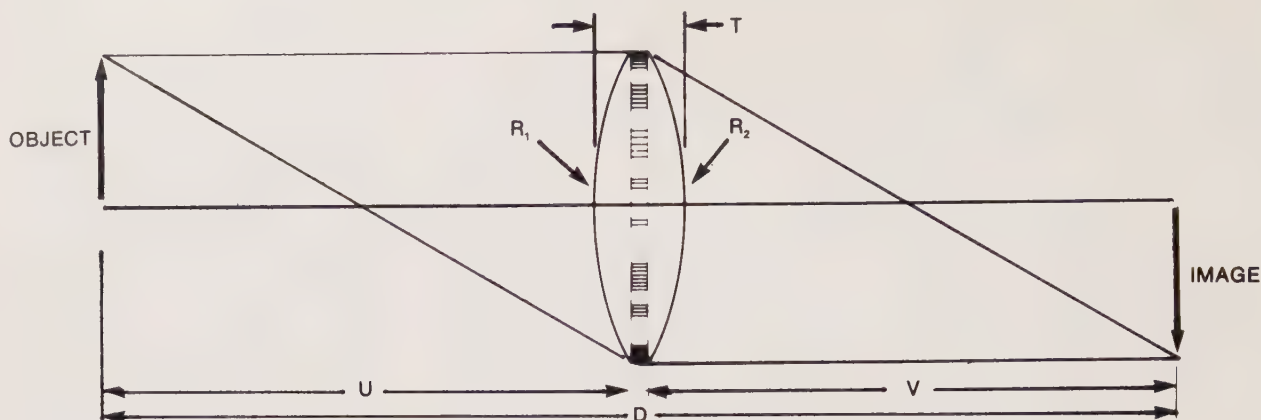
Critical Angle (Glass-to-Air)



The Distribution of Illumination in the Airy Disk



Common Lens Formulae



F = Focal Length	D = Distance object - image
M = Magnification	U = Distance object - lens
R = Reduction	V = Distance lens - image
R_1 = Radius 1	R_2 = Radius 2
T = Lens Thickness	N = Index of refraction

FOCAL LENGTH:

$$F = \frac{D \times M}{(M+1)^2}$$

$$F = \frac{U \times M}{M+1}$$

$$F = \frac{D}{M+2}$$

LENS TO IMAGE DISTANCE:

$$V = U \times M$$

$$V = (F \times M) + F$$

$$V = \frac{M \times D}{M+1}$$

$$\frac{1}{F} = (N-1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \text{ For Thin Lenses}$$

$$\frac{1}{F} = (N-1) \left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{T(N-1)}{R_1 R_2 N} \right] \text{ For Thick Lenses}$$

OBJECT TO IMAGE DISTANCE:

$$D = F \left(M + \frac{1}{M} + 2 \right)$$

$$D = \frac{V(M+1)}{M}$$

$$D = F(M+2)$$

MAGNIFICATION:

$$M = \frac{V}{U}$$

$$M = \frac{F}{U-F}$$

$$M = \frac{V-F}{F}$$

REDUCTION:

$$R = \frac{U}{V}$$

$$R = \frac{U-F}{F}$$

$$R = \frac{F}{V-F}$$

RELATIVE APERTURE (f/number)

$$f/ = \frac{\text{Focal Length}}{\text{Diameter (or clear lens aperture)}}$$

NUMERICAL APERTURE:

$$\text{N.A.} = N \sin U$$

N is refractive index of medium surrounding image (normally air where $N = 1$)

U is half the total aperture acceptance angle

LENS TO OBJECT DISTANCE:

$$U = \frac{V}{M}$$

$$U = \frac{F}{M} + F$$

$$U = \frac{D}{R+1}$$

$$\text{For infinite object distance } f/ = \frac{1}{2 \text{ N.A.}}$$

Aberration vs. Aperture vs. Field Size

Aberration

Spherical (longitudinal)
Spherical (transverse)
Coma
Petzval curvature
Astigmatism
Length of astigmatic lines
Distortion (linear)
Distortion (percentage)
Axial Chromatic (longitudinal)
Lateral Chromatic

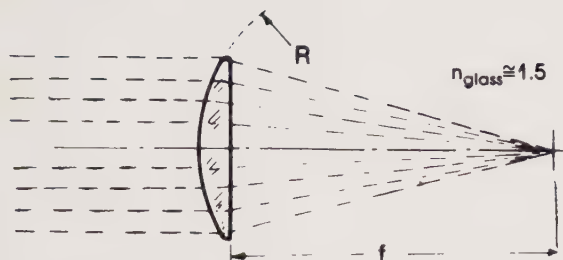
vs. Aperture

y^2
 y^3
 y^2
—
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 y
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—

vs. Field Size

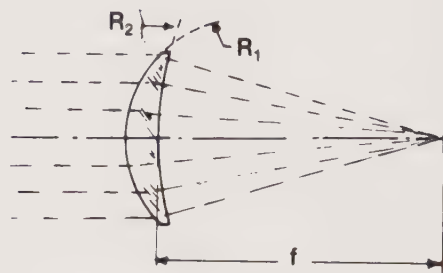
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Simple Lens Approximations



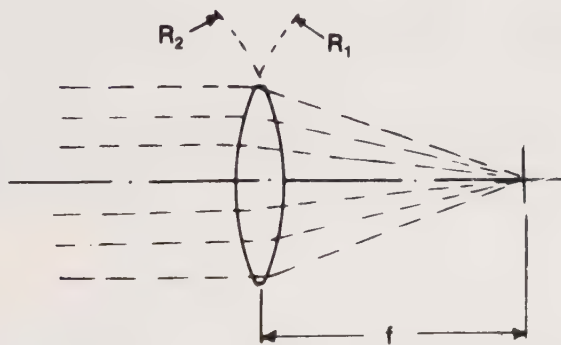
FOR THE PLANO-CONVEX LENS, THE FOCAL LENGTH EQUALS TWICE THE RADIUS OF THE CONVEX SURFACE. THIS IS ALSO TRUE FOR THE PLANO-CONCAVE; HOWEVER, SINCE THE RADIUS IS NEGATIVE, THIS RESULTS IN A NEGATIVE FOCAL LENGTH:

$$f = 2R$$



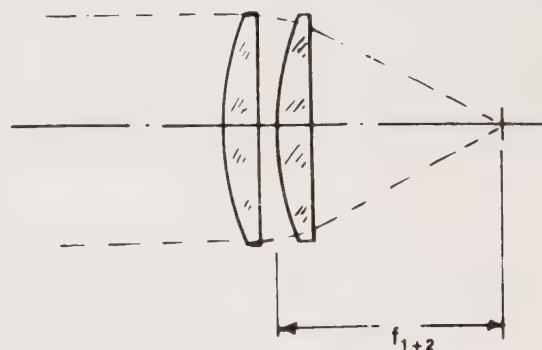
FOR OTHER FORMS OF SIMPLE LENSES, THE FOLLOWING APPLIES (NOTE: θ = POWER):

$$\frac{1}{\text{EFL}} = \theta = \frac{1}{2} \left(\frac{1}{R_1} - \frac{1}{R_2} \right)$$



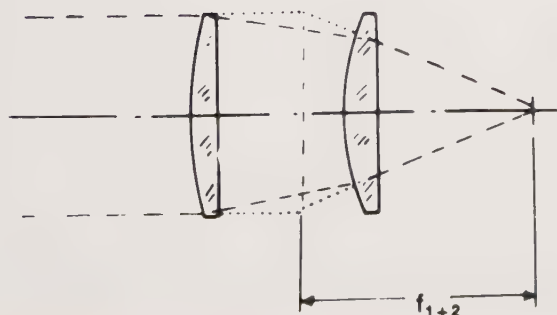
FOR THE DOUBLE-CONVEX OR DOUBLE-CONCAVE LENS HAVING EQUAL RADII, THE FOCAL LENGTH WILL EQUAL THE RADIUS:

$$R_1 = R_2 = f$$



IF TWO OR MORE THIN LENSES ARE STACKED CLOSE TOGETHER, THEIR POWERS, (1/EFL), MAY BE ADDED:

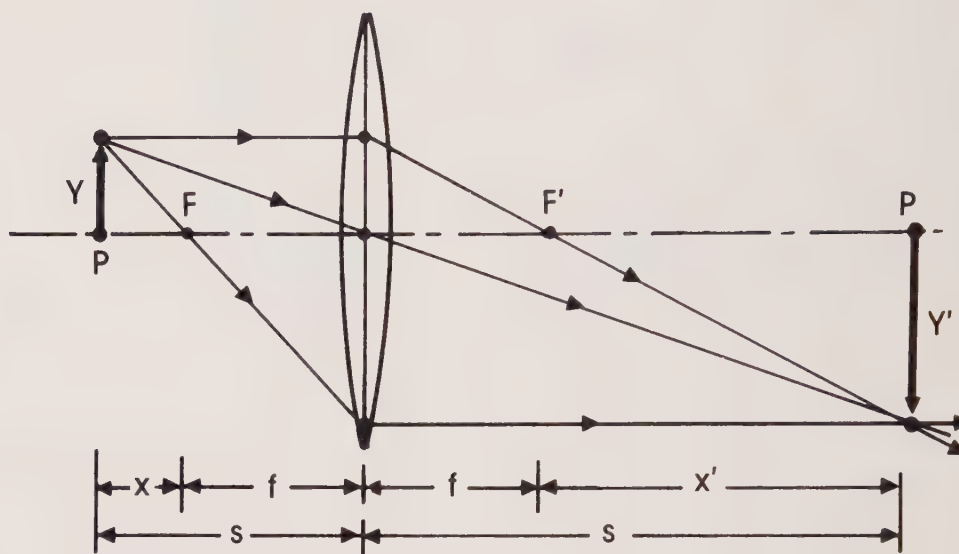
$$\theta_{(1+2)} = \theta_1 + \theta_2, \quad f_{(1+2)} = \frac{f_1 \cdot f_2}{f_1 + f_2}$$



IF A SUBSTANTIAL SEPARATION "d" EXISTS BETWEEN LENSES, THEN:

$$f_{(1+2)} = \frac{f_1 \cdot f_2}{f_1 + f_2 - d}$$

Gaussian and Newtonian Thin Lens Formulae



$$(1) \frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

$$(2) xx' = f^2$$

$$(3) m = -\frac{s'}{s}$$

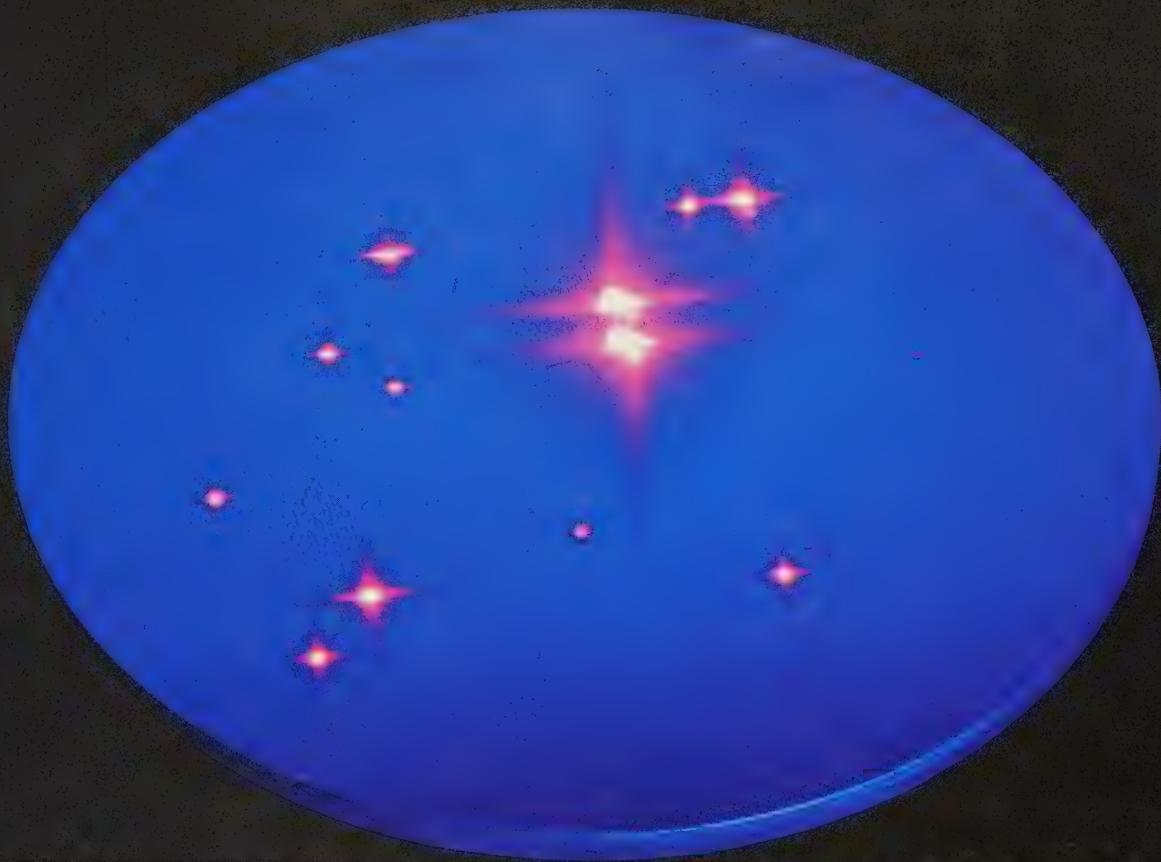
$$(4) m = -\frac{f}{x} = -\frac{x'}{f}$$

Shown above are four important equations from which the image distance and the lateral magnification can be computed for an object at any arbitrary distance from a thin lens.

Equation (1) is known as the Gaussian form of the lens equation, after the mathematician Karl F. Gauss. Equation (2), first derived by Sir Isaac Newton, is the Newtonian form of a lens equation. The Gaussian form is probably more familiar, but

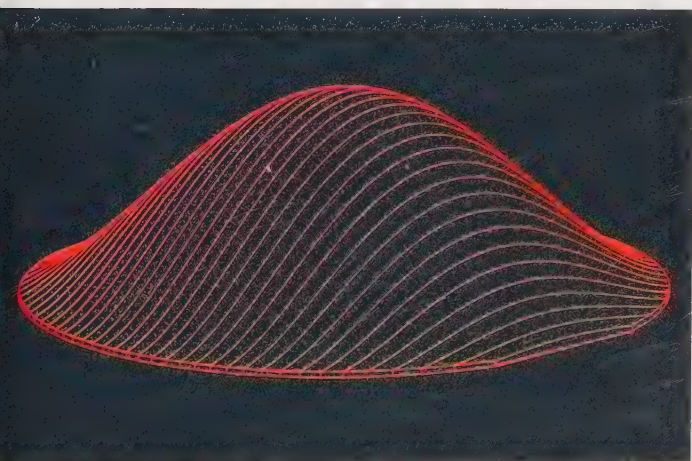
the Newtonian equation is algebraically simpler. Notice that in the former equation object and image distances s and s' are measured from the center of a thin lens, while in the latter, object and image distances x and x' are measured from the focal points F and F' .

The lateral magnification m can be expressed either in terms of s and s' , by equation (3), or in terms of x , x' , and f , by equation (4).



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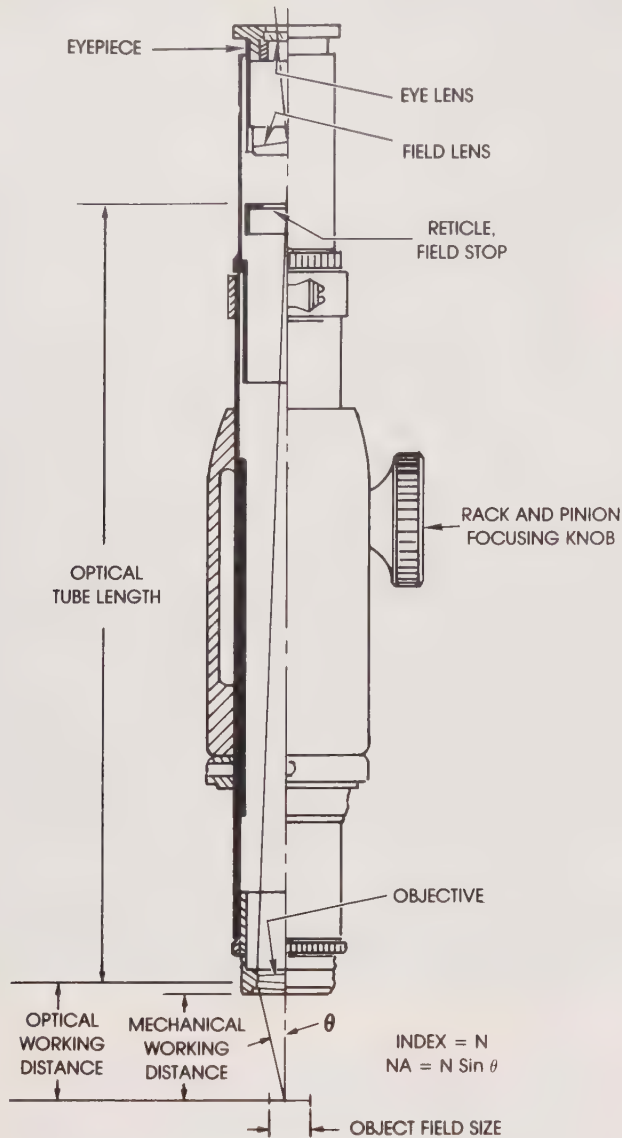
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COMPANY**



Optics of the Microscope

MICROSCOPE EYEPIECES

Magnification	Equivalent Focal Length (mm)	Diameter of Field (mm)
RAMSDEN EYEPIECES		
20X	12	10
14X	18	10
10X	25	11
6.7X	38	14
5X	50	14
ORTHOSCOPIC EYEPIECES		
14X	18	10
10X	25	12
WIDE FIELD EYEPIECE		
10X	25	22

$$\text{Object Field Size} = \frac{\text{Eyepiece Field Diameter}}{\text{Objective Magnification}}$$

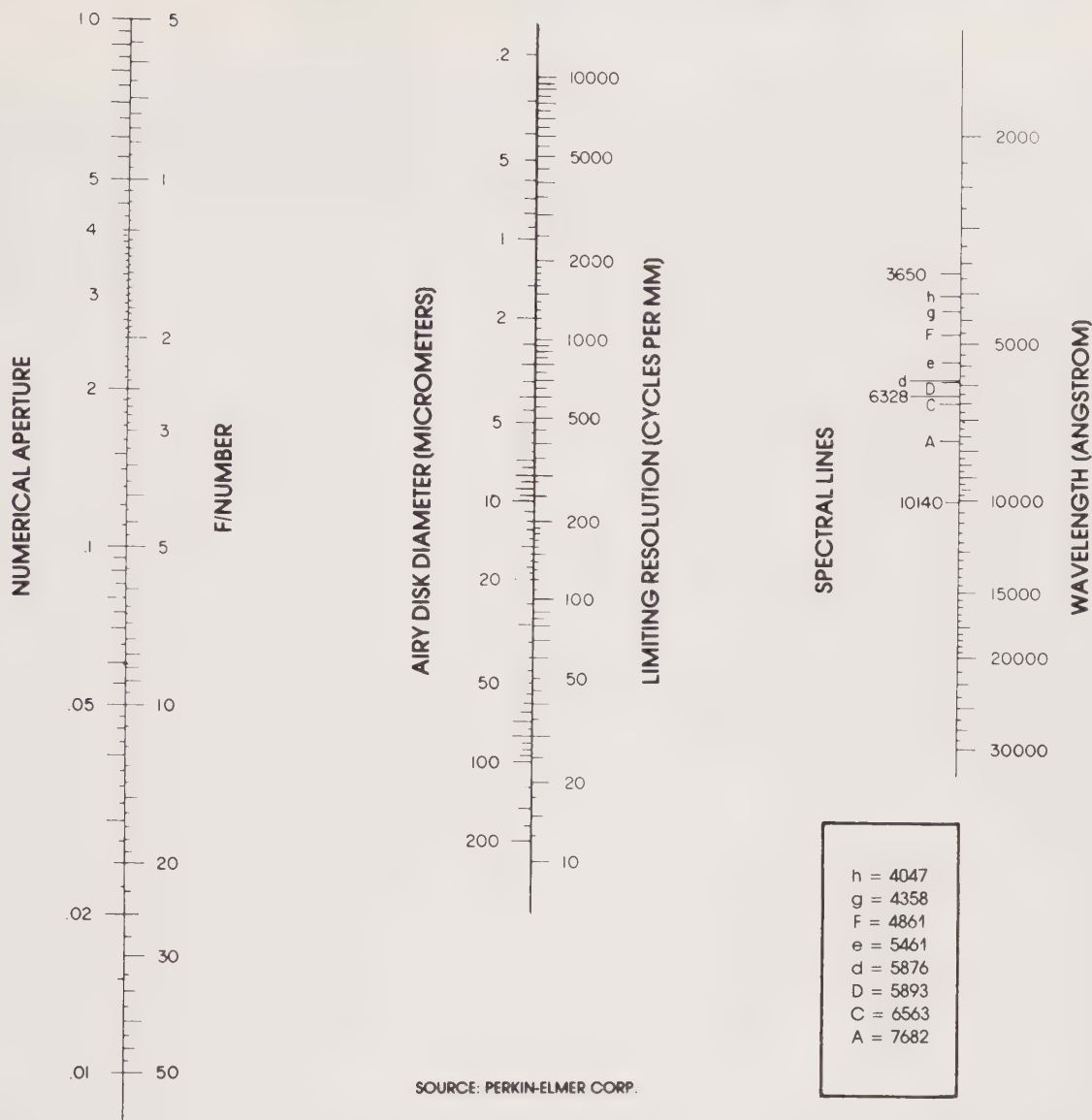
$$\text{Objective Magnification} = \frac{\text{Optical Tube Length}}{\text{Optical Working Distance}}$$

$$\text{Overall Magnification} = \text{Objective Magnification} \times \text{Eyepiece Magnification}$$

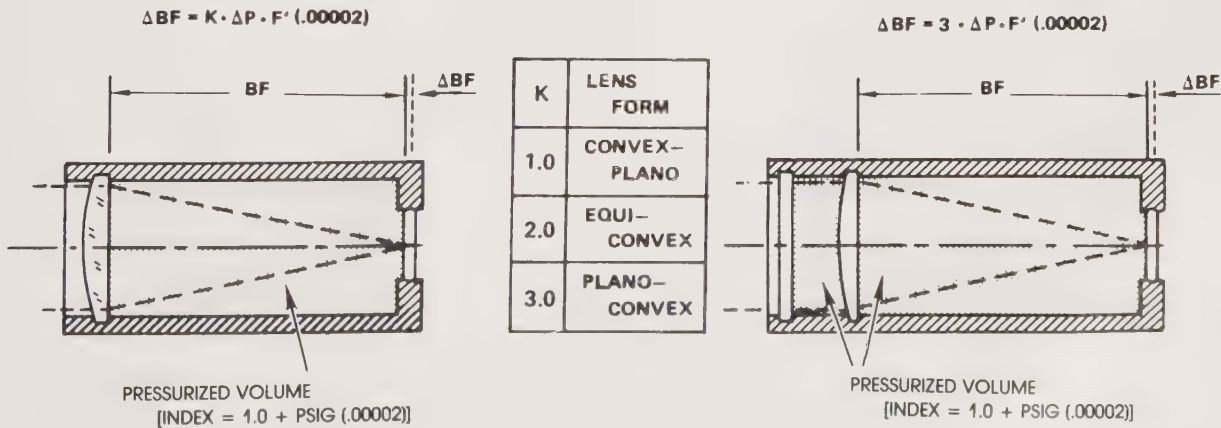
MICROSCOPE OBJECTIVES

Type	Power N/A	Focal Length (mm)		Mechanical Working Distance (mm)
		Nominal	EFL	
Achromatic, Dry	3.5/ 07	40	29.3	20.0
	5/ 12	32	24.8	27.4
	10/ 25	16	14.6	7.3
	10/ 17	16	13.9	13.6
	20/ 54	8	8.4	1.6
	20/ 54	8	8.4	1.6
	45/ 65	4	4.4	0.7
	45/ 65	4	4.4	0.7
Achromatic, Oil	100/ 1.00	2	2.1	0.3
Fluorite, Oil	45/ 95	4	4.0	0.4
Fluorite, Water	45/ 95	4	4.0	0.4
Apochromatic, Dry	10/ 35	16	14.9	10.4
	20/ 65	8	7.8	1.2
	20/ 65	8	7.8	1.2
	40/ 95	4	4.2	0.3
	40/ 95	4	4.2	0.3
	40/ 95	4	4.2	0.3
Apochromatic, Oil	90/ 1.30	2	1.9	0.3

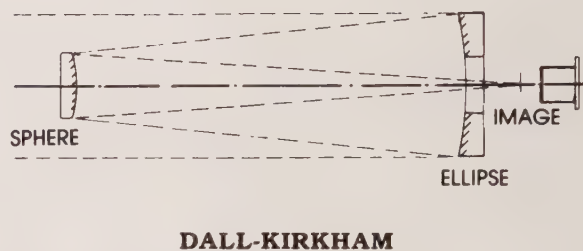
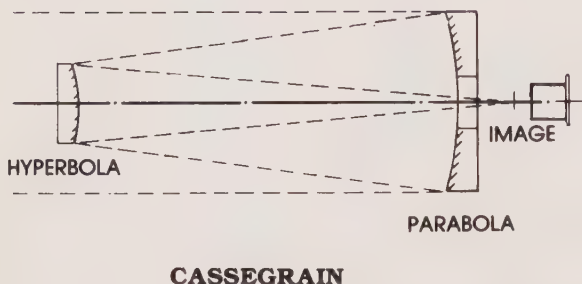
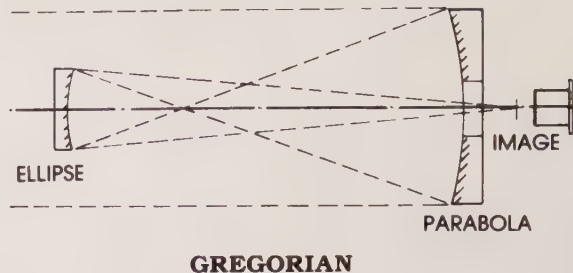
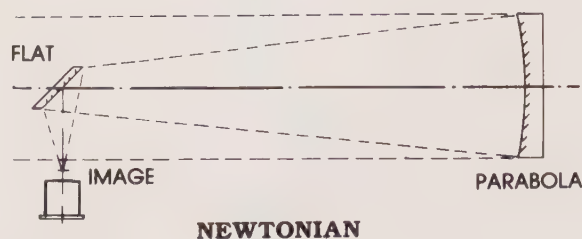
Limiting Resolution Nomogram



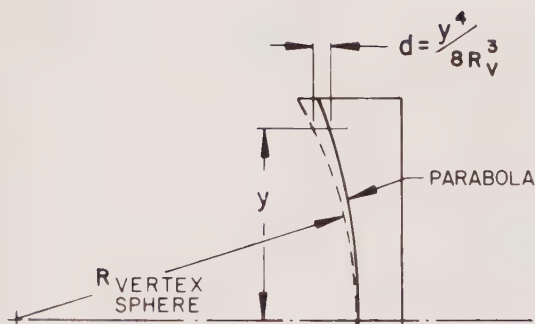
Pressurization



Reflectors in Optical Systems



All forms of reflecting telescopes utilize conic reflectors. A few of the more common forms are shown here.



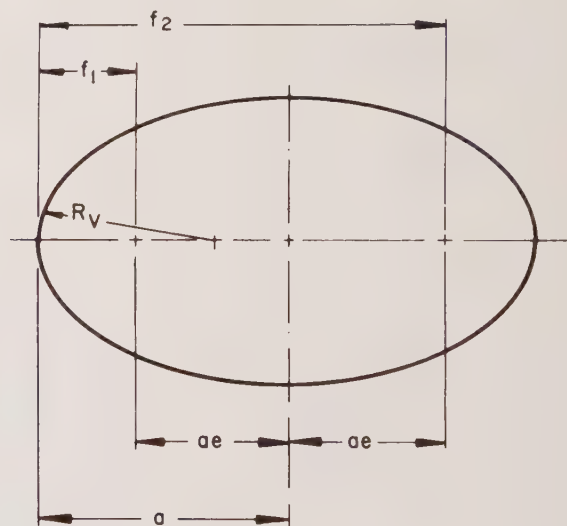
$$S = R - \sqrt{R^2 - y^2}$$

For Sphere

$$S = \frac{y^2}{2R}$$

For Parabola

Where: R = Vertex Radius
Y = Height On Curve
S = Depth Of Curve
d = Difference Between Parabola and Sphere



R_v = Vertex Radius = $2 \times$ Desired EFL

e = Eccentricity = $\sqrt{|cc|}$

$0 < cc < 1.0$

$$a = \frac{R_v}{1 + cc}$$

$$f_1 = a - ae$$

$$f_2 = a + ae$$

The salient features of the ellipse are shown. The formulae indicate how the foci of the ellipse may be found knowing its basic optical parameters.

Light Sources

- 190 Manufacturer Quick-Reference Listing
- 191 Typical Light Source Performance Data
- 192 Miniature Incandescent Lamps
- 192 Solar Spectral Irradiance
- 193 Spectra of Commonly Used Sources



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Canrad-Hanovia, Inc.
Electro-Lite Corp.
ILC Technology, Inc.
Optical Radiation Corp.
Photon Technology International, Inc.
Vortek Industries Ltd.

Typical Light Source Performance Data

SOURCE TYPE	LUMENS/ WATT (1 pw)	APPARENT COLOR TEMP (°K)	SOURCE SIZE OR TYPE	AVERAGE LUMINANCE (cd/mm ²)
NATURAL (observed from earth)				
Sun	—	5900K	—	1600
Moon	—	—	—	0.0025
Clear Sky	—	12,000 to 25,000K	—	0.008
Overcast Sky	—	6500K	—	0.002
Lightning Flash	—	—	—	8x10 ⁴
COMBUSTION				
Candle Flame	—	2000K	5x5mm	0.01
Kerosene Flame	—	—	8x8mm	0.012
Natural Gas Flame	—	—	12x12mm	0.004
Acetylene Flame	—	—	4x4mm	0.11
Photoflash Lamp	—	3800K	varies	160 to 400
NUCLEAR				
Atomic Fission Bomb	—	—	30 dia.	2x10 ⁶
Self-Luminous Paints	—	—	—	2 or 3x10 ⁻⁷
CARBON ARC				
Flame	18	3800K	5x5mm	180
High Intensity	22	5500-6500K	8x8mm	500 to 1500
ENCLOSED ARC				
Compact High Pressure				
Mercury (100W)	20	8000K	0.25x0.2mm	1700
Mercury (200W)	50	8000K	0.6x2.2mm	400
Mercury-Xenon (1000W)	50	7000K	1.5x4.2mm	350
Xenon (150W)	19	6000K	0.5x1.9mm	180
Xenon (1600W)	37.5	6000K	1.4x4.0mm	800
Xenon (20,000W)	57	6000K	3x11mm	4800
Metal Halide				
HMI (1200W)	92	5600K	2.5x13mm	120
CSI (1000W)	80	4200K	5x9mm	80
CID (1000W)	62	5500K	5x9mm	65
MARC 300	45	5000K	1x3mm	400
Zirconium	2.5	3200K	1.5mm dia.	46
Argon	17	7000K	3x10mm	1400
High Intensity Discharge (HID)				
Clear Mercury (400W)	52	6000K	20x68mm	1.5
Metal Halide (400W)	85	4500K	20x40mm	4.2
High Pressure Sodium (400W)	125	2100K	8.8x87mm	6.5
Low Pressure				
Fluorescent (cool white)				
430 ma	80	4300K	T12 Bulb	0.008
800 ma	82	4300K	T12 Bulb	0.011
1500 ma	70	4300K	T12 Bulb	0.017
Sodium	150	1700K	—	0.1
ELECTROLUMINESCENT				
Green @ 60 Hertz	—	—	—	3x10 ⁻⁵
Green @ 400 Hertz	—	—	—	7x10 ⁻⁵
INCANDESCENT				
Carbon Filament	3	2000K	C6 or C8	0.5
Tantalum Filament	6	2200K	C6 or C8	0.7
Tungsten Filament				
Vacuum Lamp	10	2600K	C6 or C8	2.0
Gas Filled Lamps	20	3000K	CC6 or CC8	12
(includes tungsten	26	3200K	CC6 or CC8	24
halogen lamps)	33	4300K	CC6 or CC8	36

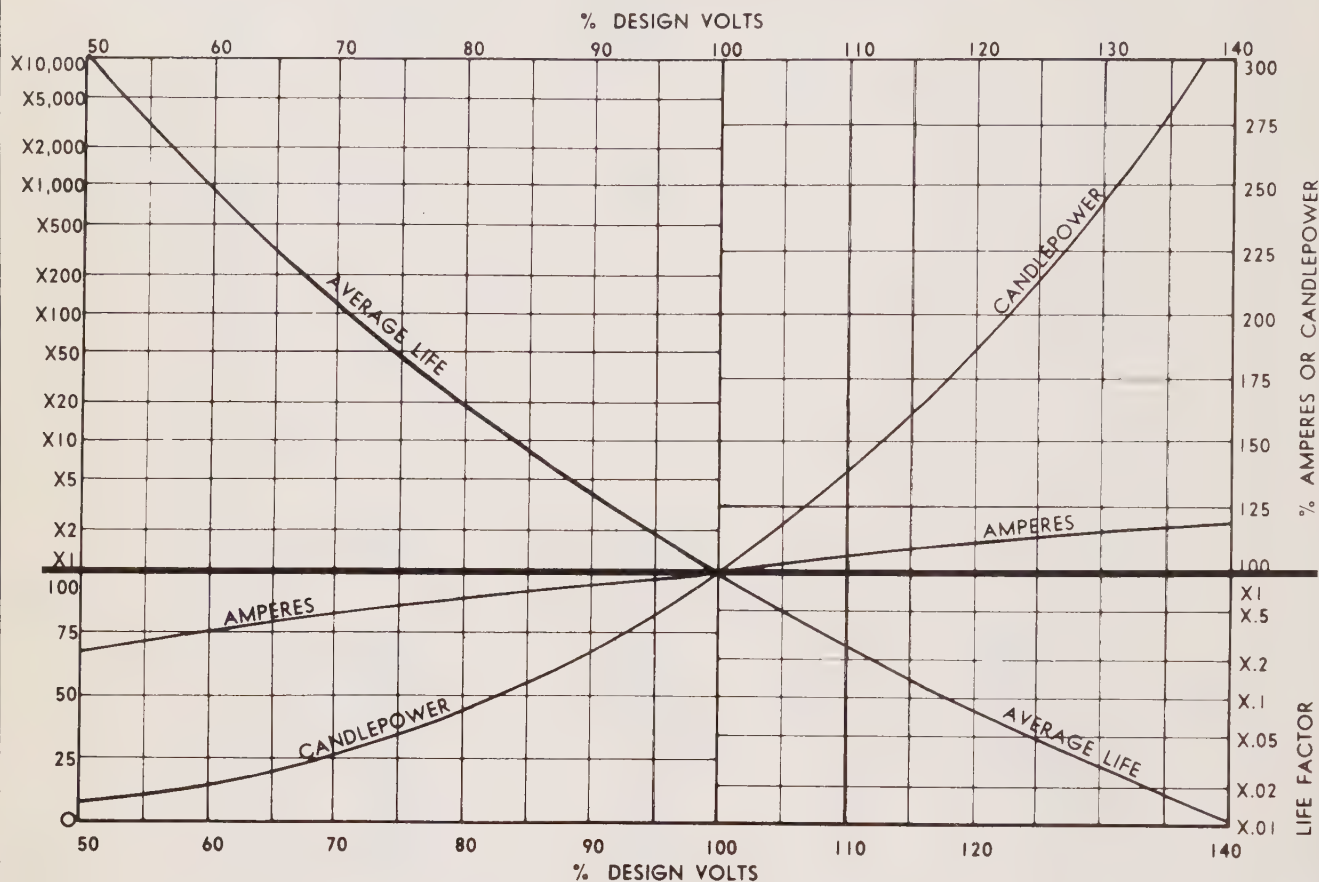
Characteristics of Miniature Incandescent Lamps

The graph below relates light output, current and life of incandescent lamps with rated (design) voltage. The curves show that the light output varies directly as the applied voltage raised to the 3.4th power, while life is inversely proportional to applied voltage raised to the 12th power.

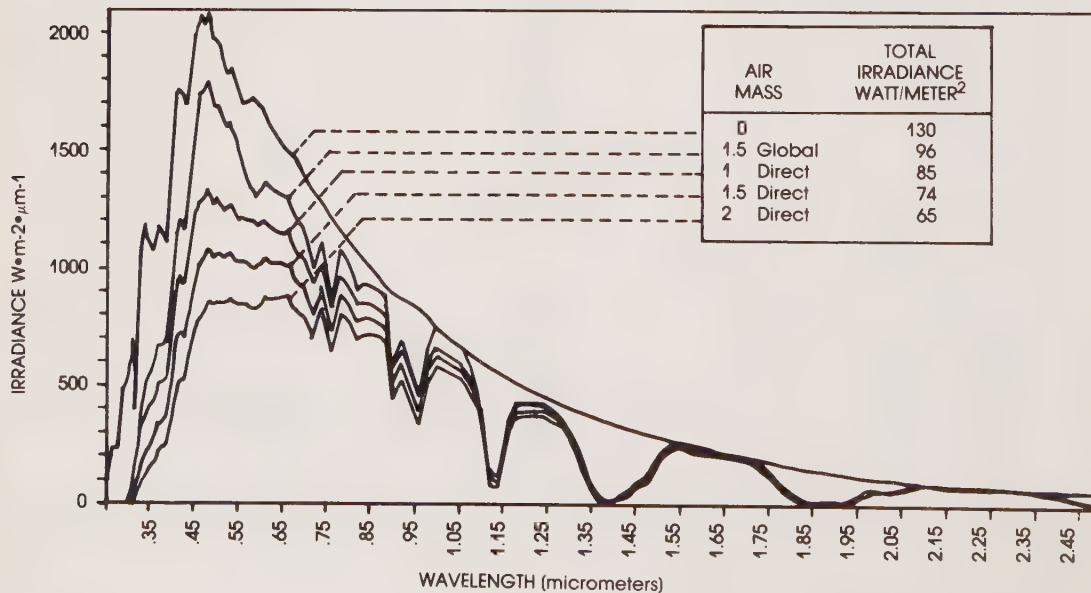
For example: at 110 percent of rated voltage, the current will

increase by 5 percent, light output increases by 40 percent, and life will be reduced to nearly 35 percent of that at design voltage.

At 80 percent of rated voltage, current decreases by 10 percent, light output drops by more than 50 percent, but lamp life is increased to 18 times normal.



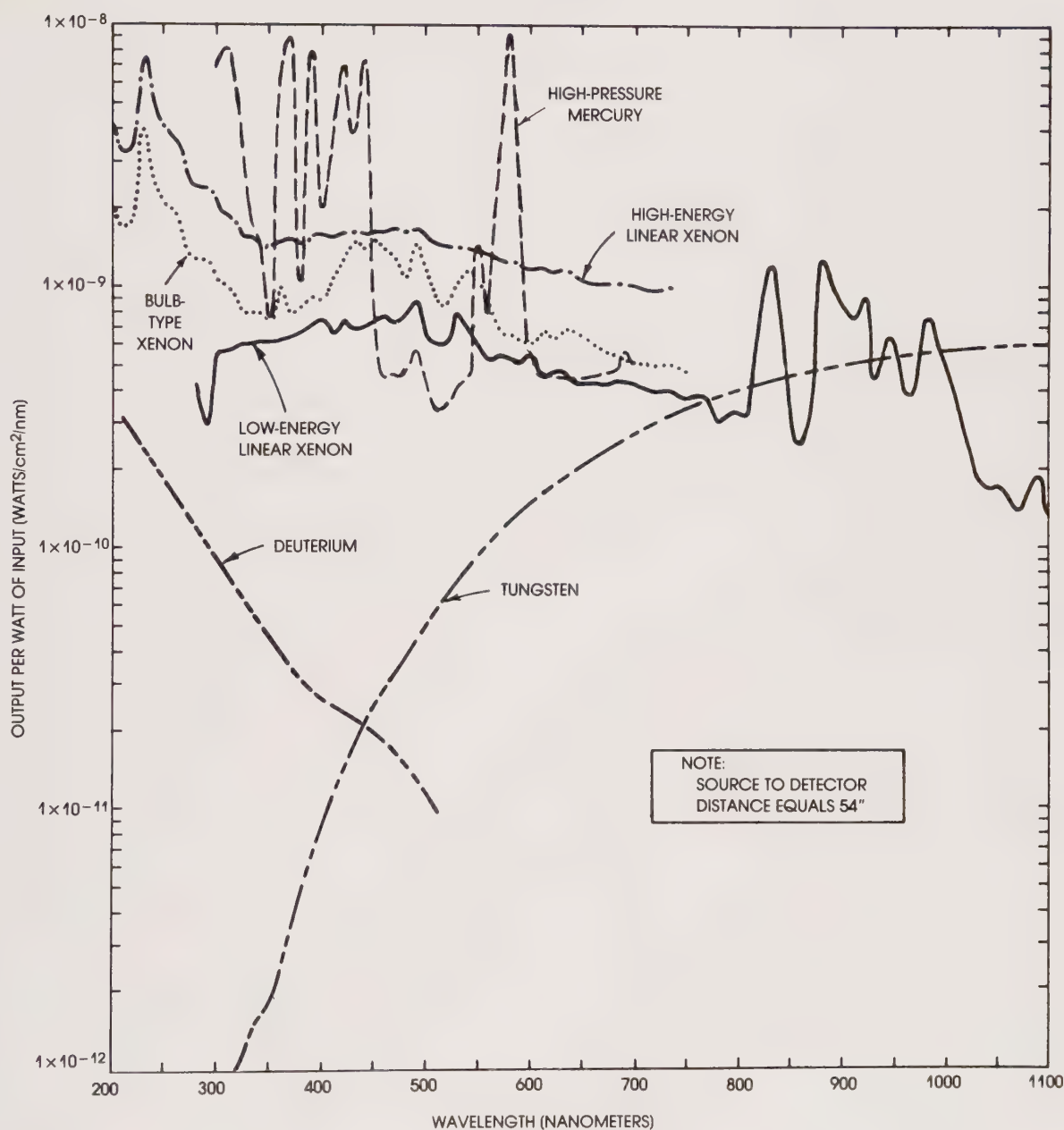
Solar Spectral Irradiance



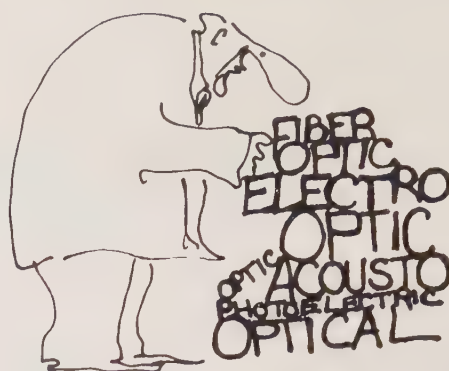
Curves supplied by Oriel Corporation from data from ASTM E490-73a for air mass zero and from Solar Energy Research Insti-

tute (SERI) for other air mass values. Data plotted with 10nm resolution to 660nm, 20nm to 1620nm and 40nm beyond 1620nm.

Spectral Characteristics of Commonly Used Optical Sources



Source: EG&G Electro-Optics Inc



Photonics — the technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon. The range of applications of photonics extends from energy generation to communications and information processing.

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Materials

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- 204 "Select" Optical Glass Types
- 206 Fused Silica: Refractive Indices
- 207 Optical Plastics
- 214 Transmission and Refractive Index for Materials
- 218 Refractive Index vs. Wavelength for Materials



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Atomergic Chemetals Corp.
R.P. Cargille Laboratories, Inc.
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Cedar Grove, NJ 07009
Ad Page **H-205**
Cleveland Crystals, Inc.
Corning Glass Works
 Advanced Products Dept.
CVD, Inc.
Dell Optics Co., Inc.
Deltronic Crystal Industries, Inc.
Dynasil Corp. of America
Eagle-Picher Industries, Inc.
Elgin Precision Glass
1200 East Abbott Dr.
Elgin, IL 60120
Ad Page **H-171**
Epoxy Technology, Inc.
Exotic Materials, Inc.
Glass Brokers, Inc.
Glass Fab, Inc.
Heraeus-Amersil, Inc.
Hoya Optics, Inc.
3400 Edison Way
Fremont, CA 94538
Ad Page **H-201**
Kappler Crystal Optics, Inc.
Nippon Silica Glass USA
 High Technology Materials Div.
Norland Products Inc.
Ohara Corp.
ROAG Fabrikationstechnik
Schott Glass Technologies, Inc.
400 York Ave.
Duryea, PA 18642
Ad Page **H-199**
Stefan Sydor Optics, Inc.
Thermal American Fused Quartz Co.

Glass Reference Index

The optical glass cross-reference index on the following pages is intended as an aid to the optical design engineer. Glass types are listed in order of increasing refractive index and decreasing dispersion. In looking at an optical design where only index and dispersion are listed, the manufacturer and catalog type can be found by simply scanning the cross-reference chart.

In designing a system by computer programs where, initially, index and dispersion are variables, the cat-

alog allows choice of the glass type closest to the optimized values for final interactions. For example, an optical schematic glass type 520637 is indicated for one element. The catalog indicates this is a Schott glass BK-8. If in the design of a system, the optimization indicates a desired glass with an index $n_d = 1.734000$ and the Abbé number = 50.0, the catalog indicates the nearest glass type as 734510 and the manufacturer and catalog types. Note that for glass types having an index n_f where

$2.0 \leq n_d < 3$ such as Hoya type TAFD $16n_d = 2.0187$, $\gamma_d = 27.20$, the MIL-G-174 type is listed as 019272.

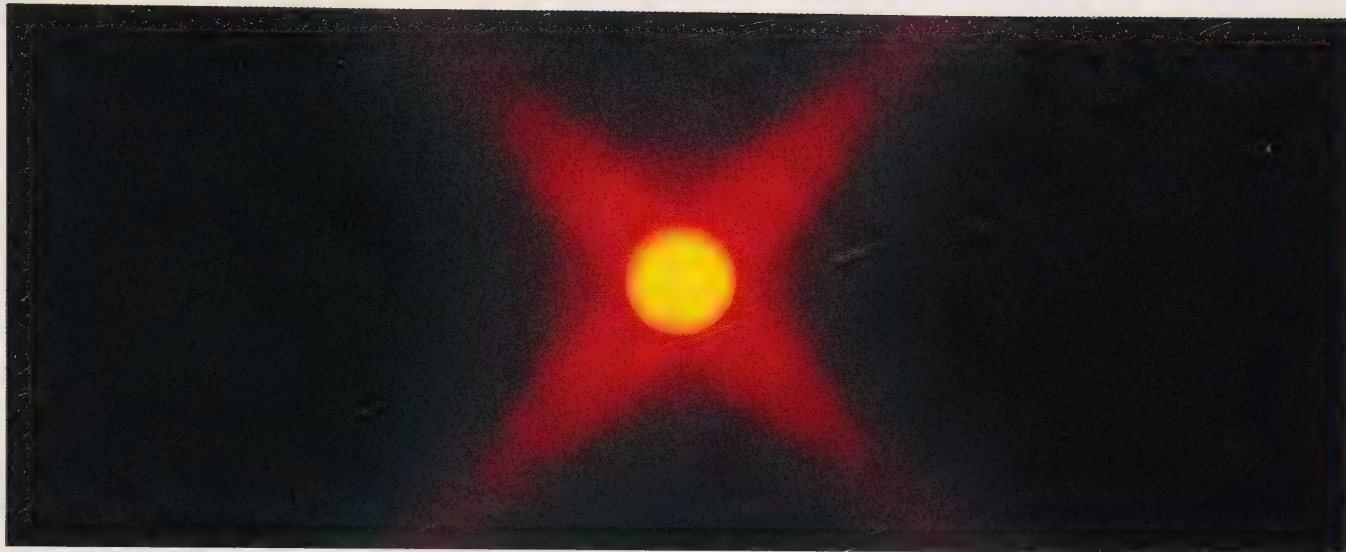
Legend

Schott Glass	Schott
Technologies Inc.	
Chance-Pilkington	Chance
Eastman Kodak	Kodak
Ohara Optical Glass Inc.	Ohara
Corning France	Corning
(Sub. of Corning Glass Works)	
Hoya Glass Works Ltd.	Hoya

MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE
437907	Schott	FK-54	510644	Chance	BSC-510644	522595	Hoya	C-5
456903	Ohara	FK-02	511510	Schott	TIF-1	522598	Ohara	K-5
458903	Hoya	FCD-10N	511510	Ohara	KF-8	523508	Ohara	KF-5
465657	Corning	A63-65	511510	Hoya	FF-1	523510	Hoya	CF-5
465658	Schott	FK-3	511604	Schott	K-7	523515	Schott	KF-9
465658	Hoya	FC-3	511605	Ohara	K-7	523585	Ohara	K-01
465659	Ohara	FK-3	511605	Hoya	C-7	523586	Hoya	C-12
471673	Schott	FK-1	512581	Ohara	ZK-4	523594	Corning	B-23-59
471673	Hoya	FC-1	515546	Hoya	CF-3	523600	Ohara	K-50
471674	Ohara	FK-1	515547	Schott	KF-3	523602	Schott	K-50
479587	Schott	TIK-1	515547	Ohara	KF-3	523604	Schott	UK-50
481817	Hoya	ADFC-10	516568	Ohara	K-2	524592	Chance	HC-524592
486818	Schott	FK-52	516641	Ohara	BK-7	525645	Ohara	PK-3
487702	Ohara	FK-5	516641	Ohara	BK-7W	525646	Hoya	PC-3
487704	Corning	A87-70	517522	Schott	KF-6	525647	Schott	PK-3
487704	Schott	FK-5	517522	Hoya	CF-6	526511	Hoya	CF-2
487704	Hoya	FC-5	517524	Ohara	KF-6	526512	Ohara	KF-2
487845	Schott	FK-51	517642	Schott	BK-7	526600	Schott	BALK-1
488658	Corning	A88-66	517642	Corning	B-16-64	526600	Ohara	BALK-1
494661	Ohara	BK-9	517642	Chance	BSC-517642	526601	Hoya	BACL-1
497816	Ohara	FK-01	517642	Hoya	BSC-7	527511	Schott	KZF-6
498650	Ohara	BK-3	517643	Schott	UBK-7	527511	Ohara	KZF-6
498651	Schott	BK-3	517696	Ohara	PKS-1	527511	Hoya	SBF-6
498651	Hoya	BSC-3	517697	Hoya	PCS-1	529516	Hoya	SBF-2
498668	Ohara	BK-10	518590	Schott	K-3	529516	Schott	KZFN-2
498670	Schott	BK-10	518590	Ohara	K-3	529517	Ohara	KZF-2
500614	Schott	K-11	518590	Hoya	C-3	529517	Schott	KZF-2
500660	Ohara	BK-4	518602	Schott	BALKN-3	529518	Corning	B-29-52
501563	Hoya	C-10	518603	Ohara	BALK-3	529770	Schott	PK-51
501564	Schott	K-10	518603	Schott	BALK-3	530512	Chance	TF-530512
501564	Ohara	K-10	518603	Corning	B-18-60	531511	Schott	KF-50
504668	Ohara	PK-1	518604	Hoya	BACL-3	531621	Schott	BK-6
504669	Schott	PK-1	518650	Ohara	PK-2	531621	Hoya	BSC-6
504669	Hoya	PC-1	518651	Schott	PK-2	531624	Ohara	BK-6
505596	Schott	K-51	518651	Corning	B-18-65	532488	Schott	LLF-6
507619	Ohara	BK-2	518652	Hoya	PC-2	532488	Hoya	FEL-6
508608	Ohara	ZKN-7	519574	Schott	K-4	532489	Ohara	LLF-6
508612	Schott	ZKN-7	519604	Chance	HC-519604	533459	Ohara	LLF-8
508612	Chance	ZC-508612	519645	Ohara	BK-12	533459	Hoya	FF-2
508613	Hoya	ZNC-7	520637	Schott	BK-8	533460	Schott	TIF-2
510621	Ohara	K-1	521526	Ohara	KZF-5	533580	Schott	ZK-1
510634	Hoya	BSC-1	521528	Hoya	SBF-5	533580	Ohara	ZK-1
510635	Schott	BK-1	521628	Schott	BK-13	533581	Hoya	ZNC-1
510635	Corning	B-10-63	521697	Schott	PK-50	534515	Hoya	CF-4
510636	Ohara	BK-1	522595	Schott	K-5	534516	Ohara	KF-4

MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE
534553	Schott	ZK-5	569561	Schott	BAK-4	589532	Ohara	BALF-6
534554	Hoya	ZNC-5	569561	Chance	MBC-569561	589610	Ohara	SK-5
534555	Ohara	ZK-5	569563	Ohara	BAK-4	589612	Corning	B-89-61
540510	Ohara	KF-1	569599	Hoya	ADC-52	589613	Schott	SK-5
540510	Hoya	CF-1	569631	Schott	PSK-2	589613	Chance	DBC-589613
540511	Schott	KF-1	569631	Hoya	PKC-2	589613	Hoya	BACD-5
540596	Ohara	BAK-2	569631	Chance	DBC-569631	592485	Schott	KZFS-6
540597	Schott	BAK-2	569632	Ohara	PSK-2	592583	Schott	SK-13
540597	Corning	B-39-59	570481	Ohara	KZF-4	592583	Hoya	BACD-13
540597	Hoya	BAC-2	570493	Ohara	BAF-2	593353	Ohara	F-16
541472	Schott	LLF-2	571508	Ohara	BALF-2	593355	Hoya	FF-5
541472	Ohara	LLF-2	571509	Schott	BALF-2	593478	Hoya	ADF-2
541472	Hoya	FEL-2	571509	Hoya	BAFL-2	594355	Schott	TIF-N5
541472	Chance	ELF-541472	571529	Schott	BALF-3	596392	Schott	F-8
547536	Schott	BALF-5	571529	Ohara	BALF-3	596392	Ohara	F-8
547536	Ohara	BALF-5	571530	Hoya	BAFL-3	596392	Hoya	F-8
548422	Schott	TIF-3	572577	Chance	MBC-572577	597553	Hoya	ADC-53
548422	Hoya	FE-3	573426	Schott	LF-1	599469	Schott	KZFS-N9
548456	Chance	ELF-548456	573426	Ohara	LF-1	601382	Schott	F-14
548457	Corning	B-48-46	573426	Hoya	FL-1	603380	Schott	F-5
548458	Schott	LLF-1	573426	Chance	LF-573426	603380	Ohara	F-5
548458	Ohara	LLF-1	573575	Corning	B-72-57	603380	Hoya	F-5
548458	Hoya	FEL-1	573575	Hoya	BAC-1	603423	Ohara	BASF-5
548535	Corning	B-48-53	573575	Schott	BAK-1	603424	Hoya	BAFD-5
548628	Ohara	PSK-1	573578	Ohara	BAK-1	603425	Schott	BASF-5
548664	Hoya	ADC-51	574520	Chance	BLF-574520	603606	Schott	SK-14
549454	Schott	LLF-7	574521	Schott	BALF-51	603606	Chance	DBC-603606
549454	Hoya	FEL-7	574564	Schott	BAK-6	603607	Ohara	SK-14
549456	Ohara	LLF-7	574564	Hoya	BAC-6	603607	Hoya	BACD-14
551495	Hoya	SBF-1	574565	Ohara	BAK-6	603654	Schott	PSK-52
551496	Schott	KZFN-1	575415	Schott	LF-7	603655	Ohara	PSK-03
551497	Schott	KZF-1	575415	Ohara	LF-7	604381	Corning	C-04-38
552634	Hoya	PCD-3	575415	Hoya	FL-7	604536	Schott	SSK-51
552635	Schott	PSK-3	578415	Ohara	LF-4	604640	Corning	CO-4-64
552637	Ohara	PSK-3	578416	Schott	LF-4	606378	Schott	F-15
554512	Schott	BALF-8	578417	Hoya	FL-4	606379	Hoya	F-15
557486	Ohara	BAF-1	579411	Chance	LF-579411	606437	Ohara	BAF-4
557586	Hoya	BAC-5	580537	Schott	BALF-4	606439	Schott	BAF-4
557587	Ohara	BAK-5	580537	Hoya	BAFL-4	606439	Corning	C-06-44
557587	Schott	BAK-5	580537	Ohara	BALF-4	606439	Chance	BF-606439
558525	Corning	B-58-53	581408	Corning	B-81-41	606439	Hoya	BAF-4
558542	Schott	KZFS-N2	581408	Ohara	LF-5	607403	Ohara	BASF-3
558673	Schott	PSK-50	581409	Schott	LF-5	607404	Hoya	BAFD-3
559713	Hoya	ADFC-14	581409	Hoya	FL-5	607492	Ohara	BAF-5
560470	Ohara	LLF-3	581409	Chance	LF-581409	607493	Hoya	BAF-5
560471	Hoya	FEL-3	582420	Hoya	FL-3	607494	Schott	BAF-5
560472	Schott	LLF-3	582421	Schott	LF-3	607567	Schott	SK-2
560612	Ohara	SK-20	582421	Ohara	LF-3	607567	Hoya	BACD-2
560612	Schott	SK-20	582421	Chance	LF-582421	607568	Ohara	SK-2
561452	Schott	LLF-4	583463	Ohara	BAF-3	607594	Ohara	SK-7
561452	Hoya	FEL-4	583465	Schott	BAF-3	607595	Schott	SK-7
561452	Ohara	LLF-4	583465	Hoya	BAF-3	607595	Hoya	BACD-7
564438	Schott	LF-8	583594	Ohara	SK-12	607595	Chance	DBC-607595
564438	Ohara	LF-8	583595	Schott	SK-12	608462	Hoya	BAF-7
564607	Ohara	SK-11	583595	Hoya	BACD-12	609464	Schott	BAF-52
564608	Schott	SK-11	584370	Schott	TIF-4	609589	Schott	SK-3
564608	Hoya	BACD-11	586610	Schott	LGSK-2	609589	Ohara	SK-3
564608	Chance	DBC-564608	589409	Schott	LF-2	609589	Hoya	BACD-3
564609	Corning	B-64-61	589410	Hoya	FL-2	609590	Corning	C-09-59
565530	Hoya	ADF-1	589411	Ohara	LF-2	610432	Hoya	ADF-3
567428	Schott	LF-6	589485	Hoya	BAF-6	610542	Hoya	ADFD-10
567428	Ohara	LF-6	589485	Schott	BAFN-6	610565	Ohara	SK-1
567428	Hoya	FL-6	589486	Ohara	BAF-6	610567	Schott	SK-1
567428	Chance	LF-567428	589512	Ohara	BALF-7	610567	Hoya	BACD-1
568580	Schott	BAK-50	589514	Schott	BALF-50	610573	Chance	DBC-610573
569560	Corning	B-69-56	589529	Hoya	BAFL-6	611558	Hoya	BACD-8
569560	Hoya	BAC-4	589530	Schott	BALF-6	611559	Schott	SK-8

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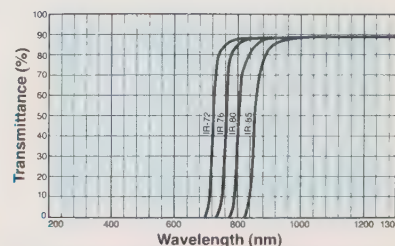
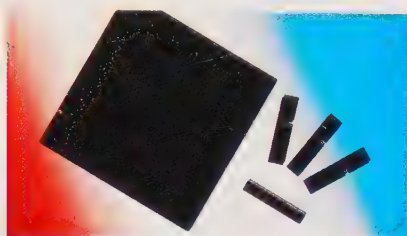
400 York Ave., Duryea, Pennsylvania 18642
(717) 457-7485 TWX 510-671-4535
Telefax (717) 457-6960

MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE
611559	Ohara	SK-8	622532	Schott	SSK-2	648339	Corning	C-48-34
613370	Schott	F-3	622532	Ohara	SSK-2	648462	Corning	C-48-46
613370	Ohara	F-3	623569	Schott	SK-10	649530	Hoya	BACED-20
613370	Hoya	F-3	623569	Corning	C-23-57	649530	Ohara	SSK-01
613438	Ohara	KZFS-4	623569	Hoya	BACD-10	650337	Schott	SF-17
613443	Schott	KZFS-1	623569	Chance	DBC-623569	650392	Schott	BASF-10
613443	Schott	KZFSN-4	623571	Ohara	SK-10	650392	Corning	C-51-39
613449	Hoya	ADF-4	623581	Schott	SK-15	650393	Hoya	BAFD-10
613574	Schott	SK-19				650394	Ohara	BASF-10
613574	Ohara	SK-19	623581	Corning	C-23-58	650557	Hoya	LACL-2
			623581	Ohara	SK-15			
613585	Corning	C-13-58	623581	Hoya	BACD-15	651383	Hoya	BAFD-4
613586	Schott	SK-4	623581	Chance	DBCT-623581	651383	Ohara	BASF-4
613586	Hoya	BACD-4	624365	Ohara	F-10	651419	Schott	BASF-57
613586	Chance	DBC-613586	624469	Corning	C-24-47	651559	Schott	LAKN-22
613587	Ohara	SK-4	624470	Schott	BAF-8	651562	Ohara	LAK-04
614439	Chance	B or F-614439	624471	Ohara	BAF-8	652449	Schott	BAF-51
614549	Ohara	SK-9	624471	Hoya	BAF-8	652584	Hoya	LAC-7
614551	Hoya	BACD-9	625356	Schott	F-7	652585	Schott	LAKN-7
614552	Schott	SK-9	625356	Hoya	F-7	652585	Chance	LAC-652585
614564	Schott	SK-6	626356	Corning	C-26-36	652585	Corning	C-52-58
614564	Corning	C-13-56	626357	Schott	F-1	652587	Ohara	LAK-7
614564	Ohara	SK-6	626357	Chance	DF-626357	653335	Chance	EDF-653335
614564	Hoya	BACD-6	626357	Ohara	F-1	654336	Ohara	SF-9
615512	Schott	SSK-3	626357	Hoya	F-1	654337	Schott	SF-9
615512	Ohara	SSK-3	626390	Schott	BASF-1	654337	Hoya	FD-9
615512	Hoya	BACED-3	626391	Hoya	BAFD-1	654396	Schott	KZFSN-5
616444	Corning	C-16-44	626392	Ohara	BASF-1	654397	Ohara	KZFS-5
617310	Schott	TIF-6	636353	Schott	F-6	655329	Schott	SF-50
617366	Schott	F-4	636353	Hoya	F-6	657367	Schott	BASF-56
617366	Ohara	F-4	636354	Ohara	F-6	658509	Schott	SSKN-5
617366	Hoya	F-4	636439	Kodak	EK-497	658509	Ohara	SSK-5
617539	Schott	SSK-1	637353	Corning	C-37-35	658509	Hoya	BACED-5
617539	Hoya	BACED-1	637491	Hoya	ADFD-11	658509	Chance	DBC-658509
617540	Ohara	SSK-1	639449	Ohara	BAF-12	658509	Schott	SSK-52
617628	Ohara	PSK-01	639451	Hoya	BAF-12	658534	Ohara	LAK-05
618498	Schott	SSKN-8	639452	Schott	BAF-12	658572	Corning	C-57-57
618498	Ohara	SSK-8	639554	Schott	SKN-18	658573	Schott	LAK-11
618526	Schott	SSK-50	639554	Ohara	SK-18	658573	Ohara	LAK-11
618550	Ohara	SSK-4	639554	Chance	DBC-639554	658573	Hoya	LAC-11
618551	Schott	SSK-4	639555	Schott	SK-52	658573	Chance	LAC-658573
618551	Corning	C-17-55	639555	Corning	C-39-56	659510	Corning	C-58-51
618552	Hoya	BACED-4	639555	Hoya	BACD-18	660329	Schott	SF-51
618634	Ohara	PSK-02	640345	Ohara	SF-7	664357	Ohara	BASF-2
620363	Corning	C-20-36	640346	Schott	SF-7	664358	Schott	BASF-2
620363	Ohara	F-2	640346	Hoya	FD-7	664359	Hoya	BAFD-2
620363	Hoya	F-2	640597	Schott	LAKL-21	664489	Hoya	BAF-21
620364	Schott	F-2	640601	Ohara	LAK-01	665534	Hoya	LACL-3
620364	Chance	DF-620364	640602	Hoya	LACL-6	667330	Schott	SF-19
620381	Schott	F-9	641568	Hoya	LACL-1	667330	Ohara	SF-19
620381	Ohara	F-9	641569	Ohara	LAK-013	667331	Corning	C-67-33
620381	Hoya	F-9	641601	Schott	LAK-21	667331	Hoya	FD-19
620497	Ohara	SSK-9	641601	Corning	C-41-60	667482	Schott	BAF-54
620498	Hoya	BACED-9	641601	Chance	LAC-641601	667483	Ohara	BAF-11
620598	Hoya	BACD-165	643478	Ohara	BAF-9	667483	Hoya	BAF-11
620601	Schott	SK-55	643479	Hoya	BAF-9	667484	Schott	BAFN-11
620603	Schott	SK-16	643480	Schott	BAF-9	667484	Corning	C-67-48
620603	Corning	C-20-60	643580	Schott	LAKN-6	668419	Schott	BASF-6
620603	Chance	DBC-620603	643580	Chance	LAC-643580	668419	Ohara	BASF-6
620603	Ohara	SK-16	643580	Hoya	LAC-6	668419	Hoya	BAFD-6
620603	Hoya	BACD-16	643584	Ohara	LAK-6	669449	Hoya	BAF-13
620635	Schott	PSK-53	646341	Schott	SF-16	669450	Schott	BAF-13
621359	Ohara	F-11	648338	Schott	SF-12	669450	Ohara	BAF-13
621360	Hoya	F-11	648338	Chance	EDF-648338	669574	Schott	LAK-23
621362	Schott	FN-11	648338	Ohara	SF-2	669574	Chance	LAC-669574
621603	Schott	SK-51	648338	Hoya	FD-2	670392	Schott	BASF-12
622360	Schott	F-13	648338	Hoya	FD-12	670393	Ohara	BASF-12
622531	Hoya	BACED-2	648339	Schott	SF-2	670471	Schott	BAFN-10

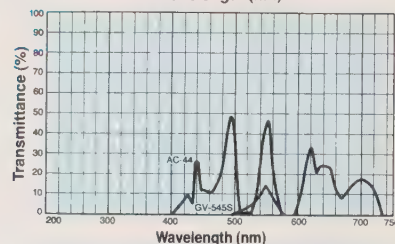
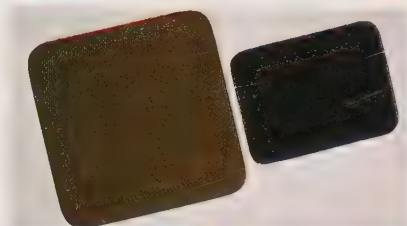
20,000,000 Hoya filters were specified last year

Engineers specify Hoya filters for a multitude of applications because of our precision controlled transmission characteristics and superior quality.

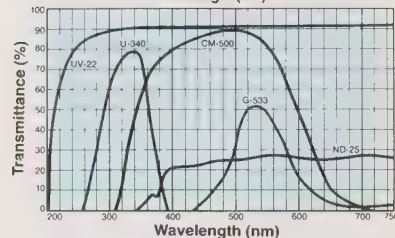
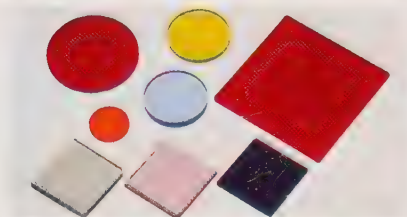
Military guidance Night vision



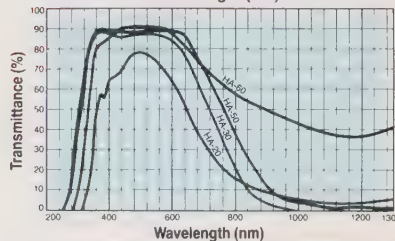
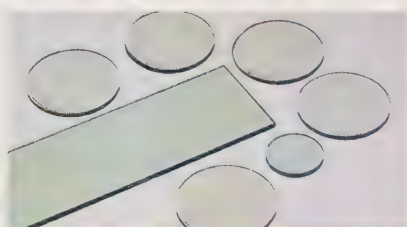
Avionics Contrast Enhancement



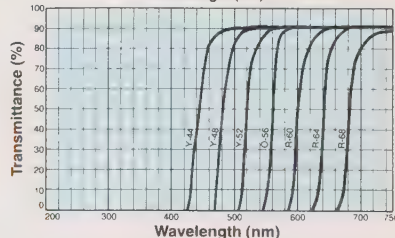
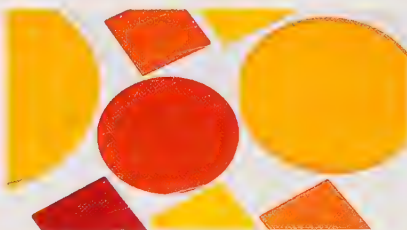
Instrument, Medical detectors, Solar



IR absorbing, Laser protective, Heat filter



Aerial camera Sharp cut filters



Last year over 20 million Hoya Optics glass filters were specified and delivered for industrial, scientific, and commercial applications.

Innovative research and new product development by Hoya gives design engineers the colored glass filters they demand and can count on.

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Please write or call for technical data and a quotation. We offer prompt response and fast delivery, with quality assurance you can depend on.

HOYA OPTICS

LOOKING BEYOND THE HORIZON

MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE
670471	Schott	BAF-53	697562	Chance	LAC-697562	724381	Schott	BASF-51
670471	Corning	C-70-47	697564	Schott	LAK-31	726534	Hoya	TAC-1
670472	Hoya	BAF-10	697565	Ohara	LAK-014	726536	Ohara	LAK-010
670473	Ohara	BAF-10	697652	Corning	C-97-56	728283	Corning	D-28-28
670516	Ohara	LAK-03	698386	Schott	BASF-13	728283	Hoya	FD-10
670517	Hoya	LACL-4	699301	Schott	SF-15	728284	Schott	SF-10
670573	Ohara	LAK-02	699301	Corning	C-99-30	728284	Chance	DEDF-728284
670573	Hoya	LACL-7	699301	Ohara	SF-15	728285	Ohara	SF-10
673289	Schott	TISF-1	699301	Hoya	FD-15	728287	Schott	SF-53
673321	Ohara	SF-5	699301	Chance	EDF-699301	728287	Hoya	FDS-2
673322	Schott	SF-5	700347	Schott	BASF-55	729547	Ohara	LAK-18
673322	Hoya	FD-5	700349	Hoya	BAFD-14	734265	Corning	D-34-26
673323	Corning	C-72-32	700350	Schott	BASF-14	734510	Kodak	EK-215
673363	Hoya	ADF-6	700412	Chance	BF-700412	734511	Hoya	TAC-4
678506	Hoya	LACL-9	700478	Hoya	LAF-3	734514	Corning	D-34-51
678507	Ohara	LAK-06	700481	Ohara	LAF-01	734515	Ohara	LAK-09
678534	Ohara	LAK-07	701396	Schott	BASF-64	734517	Schott	LAKN-16
678534	Hoya	LACL-8	702402	Hoya	BAFD-15	734517	Chance	LAC-734517
678552	Schott	LAKN-12	702410	Schott	BASF-52	735411	Ohara	LAF-8
678552	Chance	LAC-678552	702410	Chance	BF-702410	735416	Schott	LAFN-8
678553	Ohara	LAK-12	702411	Corning	D-01-41	735498	Ohara	LAF-03
678555	Corning	C-78-56	702412	Ohara	BASF-7	735498	Hoya	NbF-3
678555	Hoya	LAC-12	702412	Ohara	BASF-07	736322	Schott	BASF-54
681319	Schott	SF-62	702412	Hoya	BAFD-7	740281	Corning	D-40-28
681372	Schott	KZFSN-7	706300	Chance	EDF-706300	740282	Schott	SF-3
682482	Schott	LAF-20	706303	Schott	SFN-64	740282	Hoya	FD-3
683445	Schott	BAF-50	710366	Schott	BASF-50	740283	Ohara	SF-3
683447	Ohara	BAF-01	713432	Ohara	LAF-07	741276	Schott	SF-13
686439	Hoya	BAF-20	713433	Hoya	LAF-4	741278	Ohara	SF-13
686440	Ohara	BAF-03	713538	Schott	LAK-8	741278	Hoya	FD-13
686492	Ohara	LAF-06	713538	Corning	D-13-54	741281	Schott	SF-54
686494	Hoya	LAF-1	713538	Chance	LAC-713538	741281	Chance	DEDF-741281
687428	Hoya	ADFD-13	713538	Ohara	LAK-8	741526	Hoya	TAC-2F
689306	Schott	SF-52	713539	Hoya	LAC-8	741527	Ohara	LAK-011
689311	Ohara	SF-8	717295	Schott	SF-1	743492	Hoya	NbF-1
689312	Schott	SF-8	717295	Corning	D-17-29	743493	Ohara	LAF-010
689312	Corning	C-89-31	717295	Ohara	SF-1	744447	Ohara	LAF-2
689312	Hoya	FD-8	717295	Hoya	FD-1	744447	Schott	LAF-2
689495	Schott	LAF-23	717295	Chance	DEDF-717295	744448	Chance	LAF-744448
689495	Chance	LAFA-689495	717479	Chance	LAF-717479	744448	Schott	LAFN-2
689496	Corning	C-90-50	717479	Ohara	LAF-3	744448	Corning	D-44-45
689497	Schott	LAFN-23	717480	Schott	LAF-3	744449	Hoya	LAF-2
691540	Corning	C-91-54	717480	Schott	LAFN-3	744508	Schott	LAK-28
691547	Schott	LAK-9	717480	Corning	D-17-48	745439	Kodak	EK-415
691547	Chance	LACA-691547	717480	Hoya	LAF-3	745456	Kodak	EK-325
691547	Hoya	LAC-9	717480	Chance	LAF-717480	746400	Schott	LAF-26
691548	Corning	C-90-55	720293	Ohara	SF-01	748277	Schott	SF-63
691548	Ohara	LAK-9	720293	Hoya	FD-20	748278	Chance	DEDF-748278
691548	Chance	LACB-691548	720346	Schott	KZFS-8	749350	Ohara	LAF-015
693516	Schott	LAK-20	720347	Ohara	KZFS-8	750349	Ohara	LAF-015
694508	Ohara	LAK-08	720420	Hoya	LAF-6	750350	Schott	LAFN-7
694508	Hoya	LACL-5	720420	Ohara	LAF-08	750350	Hoya	LAF-7
694532	Ohara	LAK-13	720437	Ohara	LAF-02	750353	Ohara	LAF-7
694533	Schott	LAKN-13	720439	Hoya	LAF-5	751275	Schott	SF-61
694533	Hoya	LAC-13	720460	Ohara	LAF-011	751277	Ohara	SF-04
694533	Chance	LAC-694533	720503	Corning	D-20-50	753506	Kodak	EK-230
696364	Corning	C-97-36	720503	Hoya	LAC-10	755275	Ohara	SF-4
697485	Ohara	LAF-09	720503	Ohara	LAK-10	755275	Hoya	FD-4
697485	Hoya	LAF-2	720504	Schott	LAK-10	755276	Schott	SF-4
697554	Schott	LAKN-14	720504	Chance	LAF-720504	755276	Corning	D-56-27
697554	Corning	C-97-55	722292	Ohara	SF-18	755276	Chance	DEDF-755276
697554	Chance	LAC-697554	722292	Hoya	FD-18	755523	Ohara	LASK-01
697555	Hoya	LAC-14	722293	Schott	SF-18	757318	Schott	LAFN-11
697555	Ohara	LAK-14	723379	Ohara	BASF-8	757318	Hoya	NbFD-9
697556	Kodak	EK-115	723380	Hoya	BAFD-8	757363	Hoya	NbFD-6
697561	Hoya	LAC-15	723380	Ohara	BASF-08	757477	Hoya	NbF-2
697562	Kodak	EK-110	724380	Corning	D-23-38	757478	Schott	LAF-24

MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE
757478	Schott	LAFN-24	788475	Schott	LAFN-21	834372	Ohara	LASF-010
757479	Ohara	LAF-04	788475	Hoya	TAF-4	834373	Hoya	NbFD-10
762265	Ohara	SFL-14	789428	Hoya	NbFD-1	835427	Ohara	LASF-05
762265	Schott	SF-14	795284	Schott	LAF-9	835430	Hoya	TAFD-5
762266	Ohara	SF-14	795453	Ohara	LASF-017	836302	Corning	E-37-30
762266	Hoya	FD-14	795454	Hoya	TAF-2F	838420	Hoya	TAFD-2F
762269	Corning	D-62-27	797411	Hoya	NbFD-2	841432	Ohara	LASF-06
762269	Hoya	FDS-5	800422	Ohara	LASF-02	847238	Ohara	SFL-03
762270	Schott	SF-55	800423	Hoya	NbFD-12	847238	Schott	SF-57
762271	Ohara	SFS-5	800457	Corning	E-00-46	847238	Hoya	FDS-9
762401	Ohara	LAF-05	802443	Schott	LASF-11	847239	Ohara	SF-03
762403	Hoya	NbFD-5	802443	Hoya	NbFD-14	850322	Schott	LASF-9
773496	Schott	LAFN-28	803304	Schott	LASF-32	850322	Chance	LAF-850322
773496	Hoya	TAF-1	803464	Schott	LASFN-30	850322	Hoya	TAFD-9
773497	Ohara	LASF-016	803465	Schott	LASF-30	850322	Schott	LASFN-9
776378	Schott	LAF-13	803467	Ohara	LASF-012	850323	Ohara	LASF-021
782371	Schott	LAF-22	804396	Ohara	LASF-013	855366	Schott	LASF-13
783361	Hoya	NbFD-7	804418	Kodak	EK-455	855366	Hoya	TAFD-13
783362	Ohara	LAF-012	804465	Hoya	TAF-3F	863415	Ohara	LASF-07
784413	Schott	LAF-25	804466	Ohara	LASF-015	879403	Kodak	EK-445
784439	Schott	LAFN-10	805254	Schott	SFL-6	878381	Schott	LASFN-15
785257	Ohara	SF-11	805254	Schott	SF-6	878382	Hoya	TAFD-17
785257L	Ohara	SFL-11	805254	Ohara	SF-6	881410	Schott	LASFN-31
785257	Hoya	FD-11	805254L	Ohara	SFL-6	883410	Ohara	LASF-08
785258	Schott	SF-11	805254	Chance	DEDF-805254	907383	Ohara	LASF-024
785258	Chance	DEDF-785258	805255	Corning	E-05-25	909370	Hoya	TAFD-11
785259	Corning	D-85-26	805255	Hoya	FD-6	911197	Kodak	EK-922
785261	Schott	SF-56	805396	Hoya	NbFD-3	913324	Schott	LASFN-18
785261	Schott	SFL-56	860342	Schott	LASF-33	915213	Ohara	SFS-02
785261	Hoya	FDS-3	806407	Hoya	NbFD-13	918215	Schott	SF-58
785262	Ohara	SFS-3	806409	Ohara	LASF-03	921357	Ohara	LASF-019
785263	Ohara	SFSL-3	807316	Schott	LASF-8	923209	Ohara	SFS-1
786439	Hoya	NbFD-11	807355	Hoya	NbFD-8	923213	Ohara	SFS-01
786442	Ohara	LASF-01	808406	Schott	LASF-3	943361	Kodak	EK-510
787500	Ohara	LASK-02	808408	Schott	LASFN-3	949204	Kodak	EK-812
787500	Schott	LAKN-17	815442	Hoya	TAFD-1F	953204	Schott	SF-59
788474	Schott	LAF-21	816445	Ohara	LASF-04	096195	Kodak	EK-911
788474	Ohara	LASF-014	816468	Ohara	LASF-09			
788474	Chance	LAF-788474	831365	Hoya	NbFD-4			

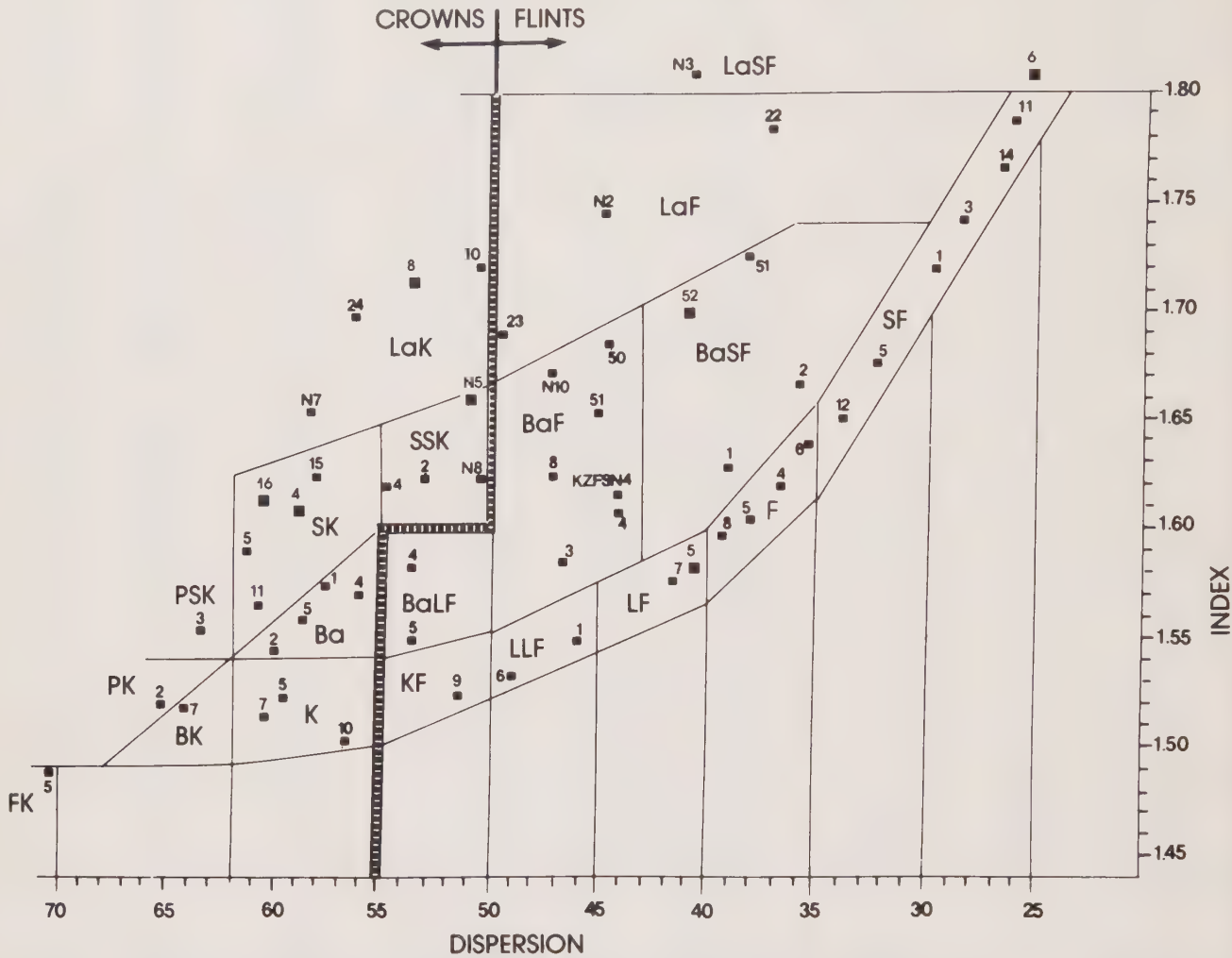
Coefficients of Expansion of Important Materials

Material	Coefficient of Expansion (10 ⁻⁶ per°C)	Material	Coefficient of Expansion (10 ⁻⁶ per°C)	Material	Coefficient of Expansion (10 ⁻⁶ per°C)
Aluminum	23.8	Glass (Jena Standard 16, Schott BK1)	8.0	Iron Steel	13.22
Aluminum/copper alloy (10% Cu.)	22.4	Glass (Jena Instrument 20, Schott K51)	4.8	Lead	27.08
Brass (cast)	18.75	Gold	13.2	Magnesium (cast)	26.96
Carbon (diamond)	1.18	Invar (36% Ni.)	.9	Nickel	10.12
Carbon (graphite)	7.86	Iron (cast)	10.0	Nickel Steel (58% Ni.)	12.0
Copper	14.09			Platinum	8.99
Formica	30.0			Quartz, fused	.55
Glass (Schott F7)	10.2			Rubber (hard)	80.0

"Select" Optical Glass Types

The approximately 250 glass types listed on the preceding pages have been examined with the goal of establishing a group of "select" glasses that offer distinct advantages in

areas such as cost, availability, workability, quality and so forth. The diagram and the table below and on the following page identify these "select" glass types.

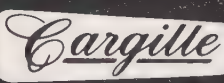


MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE
487702	Ohara	FK-5	532488	Hoya	FEL-6	564609	Corning	B-64-61
487704	Corning	A87-70	532489	Ohara	LLF-6	569560	Corning	B-69-56
487704	Schott	FK-5	540596	Ohara	BAK-2	569560	Hoya	BAC-4
487704	Hoya	FC-5	540597	Schott	BAK-2	569561	Schott	BAK-4
501563	Hoya	C-10	540597	Corning	B-39-59	569561	Chance	MBC-569561
501564	Schott	K-10	540597	Hoya	BAC-2	569563	Ohara	BAK-4
501564	Ohara	K-10	547536	Schott	BALF-5	573575	Corning	B-72-57
511604	Schott	K-7	547536	Ohara	BALF-5	573575	Hoya	BAC-1
511605	Ohara	K-7	548457	Corning	B-48-46	573576	Schott	BAK-1
511605	Hoya	C-7	548458	Schott	LLF-1	573578	Ohara	BAK-1
517642	Schott	BK-7	548458	Ohara	LLF-1	580537	Schott	BALF-4
517642	Corning	B-16-64	548458	Hoya	FEL-1	580537	Hoya	BALF-4
517642	Chance	BSC-517642	552634	Hoya	PCD-3	580537	Ohara	BALF-4
517642	Hoya	BSC-7	552635	Schott	PSK-3	581408	Corning	B-81-41
518650	Ohara	PK-2	552637	Ohara	PSK-3			
518651	Schott	PK-2	557586	Ohara	BAK-5			
518651	Corning	B-18-65	557586	Hoya	BAC-5			
518652	Hoya	PC-2	557587	Schott	BAK-5			
522595	Schott	K-5	564607	Ohara	SK-11			
522595	Hoya	C-5	564608	Schott	SK-11			
523515	Schott	KF-9	564608	Hoya	BACD-11			
532488	Schott	LLF-6	564608	Chance	DBC-564608			

Legend

Schott Glass Technologies Inc.	Schott
Chance-Pilkington	Chance
Ohara Optical Glass Manufacturing	Ohara
Corning France	Corning
Hoya Glass Works Ltd.	Hoya

MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE	MIL-G-174 TYPE	MANU- FACTURER	CATALOG TYPE
581408	Ohara	LF-5	664358	Schott	BASF-2	720503	Corning	D-20-50
581409	Schott	LF-5	664359	Hoya	BAFD-2	720503	Hoya	LAC-10
581409	Hoya	FL-5	670471	Schott	BAFN-10	720503	Ohara	LAK-10
581409	Chance	LF-581409	670471	Corning	C-70-47	720504	Chance	LAC-720504
583463	Ohara	BAF-3	670472	Hoya	BAF-10	720504	Schott	LAK-10
583465	Schott	BAF-3	670473	Ohara	BAF-10	723379	Ohara	BASF-8
583465	Hoya	BAF-3	673321	Ohara	SF-5	723380	Hoya	BAFD-8
589612	Corning	B-89-61	673322	Schott	SF-5	724380	Corning	D-23-38
589613	Schott	SK-5	673322	Hoya	FD-5	724381	Schott	BASF-51
589613	Chance	DBC-589613	673323	Corning	C-72-32	740281	Corning	D-40-28
589613	Hoya	BACD-5	683445	Schott	BAF-50	740282	Schott	SF-3
596392	Schott	F-8	683447	Ohara	BAF-01	740282	Hoya	FD-3
596392	Ohara	F-8	689495	Schott	LAF-23	740283	Ohara	SF-3
596392	Hoya	F-8	689495	Chance	LAF-689495	744448	Chance	LAF-744448
603380	Schott	F-5	689496	Corning	C-90-50	744448	Schott	LAFN-2
603380	Ohara	F-5	697561	Hoya	LAC-15	744448	Corning	D-44-45
603380	Hoya	F-5	697562	Chance	LAC-697562	744448	Ohara	LAF-2
606437	Ohara	BAF-4	697565	Ohara	LAK-014	744449	Hoya	LAF-2
606439	Schott	BAF-4	702410	Schott	BASF-52	762265	Schott	SF-14
606439	Corning	C-06-44	702410	Chance	BF-702410	762266	Ohara	SF-14
606439	Chance	BF-606439	702411	Corning	D-01-41	762266	Hoya	FD-14
606439	Hoya	BAF-4	702412	Ohara	BASF-7	782371	Schott	LAF-22
609590	Corning	C-09-59	702412	Ohara	BAF-07	785257	Ohara	SF-11
613443	Schott	KZFS-1	702412	Hoya	BAFD-7	785257	Hoya	FD-11
613586	Schott	SK-4	713538	Schott	LAK-8	785258	Schott	SF-11
613586	Hoya	BACD-4	713538	Corning	D-13-54	785258	Chance	DEDF-785258
613586	Chance	DBC-613586	713538	Chance	LAC-713538	785259	Corning	D-85-26
613587	Ohara	SK-4	713538	Ohara	LAK-8	805254	Schott	SF-6
617366	Schott	F-4	713539	Hoya	LAC-8	805254	Ohara	SF-6
617366	Ohara	F-4	717295	Schott	SF-1	805254L	Ohara	SFL-6
617366	Hoya	F-4	717295	Corning	D-17-29	805254	Chance	DEDF-805254
618550	Ohara	SSK-4	717295	Ohara	SF-1	805255	Corning	E-05-25
618551	Schott	SSK-4	717295	Hoya	FD-1	805255	Hoya	FD-6
618551	Corning	C-17-55	717295	Chance	DEDF-717295	808408	Schott	LASFN-3
618552	Hoya	BACED-4						
620603	Schott	SK-16						
620603	Corning	C-20-60						
620603	Chance	DBC-620603						
620603	Ohara	SK-16						
620603	Hoya	BACD-16						
622531	Hoya	BACED-2						
622532	Schott	SSK-2						
622532	Ohara	SSK-2						
623581	Schott	SK-15						
623581	Corning	C-23-58						
623581	Ohara	SK-15						
623581	Hoya	BACD-15						
623581	Chance	DBCT-623581						
624469	Corning	C-24-47						
624470	Schott	BAF-8						
624471	Hoya	BAF-8						
624471	Ohara	BAF-8						
626390	Schott	BASF-1						
626391	Hoya	BAFD-1						
626392	Ohara	BASF-1						
636353	Schott	F-6						
636353	Hoya	F-6						
636354	Ohara	F-6						
648338	Schott	SF-12						
648338	Chance	EDF-648338						
648338	Ohara	SF-2						
648338	Hoya	FD-2						
648338	Hoya	FD-12						
652449	Schott	BAF-51						
652584	Hoya	LAC-7						
652585	Schott	LAKN-7						
652585	Corning	C-52-58						
652587	Ohara	LAK-7						
658509	Schott	SSKN-5						
658509	Ohara	SSK-5						
658509	Hoya	BACED-5						
658509	Chance	DBC-658509						
658509	Schott	SSK-52						
664357	Ohara	BASF-2						



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Optical Properties of Fused Silica

Glass Type Number (MIL-G-174A): 458-678

Abbé Constringent Coefficient

$$\text{Helium } V_d = \frac{n_d - 1}{n_F - n_C} = 67.8 \pm .5$$

d=5876A

D=5893A

F=4861A

$$\text{Sodium } V_D = \frac{n_D - 1}{n_F - n_C} = 67.8 \pm .5$$

C=6563A

Temperature Coefficient of Refractive Index

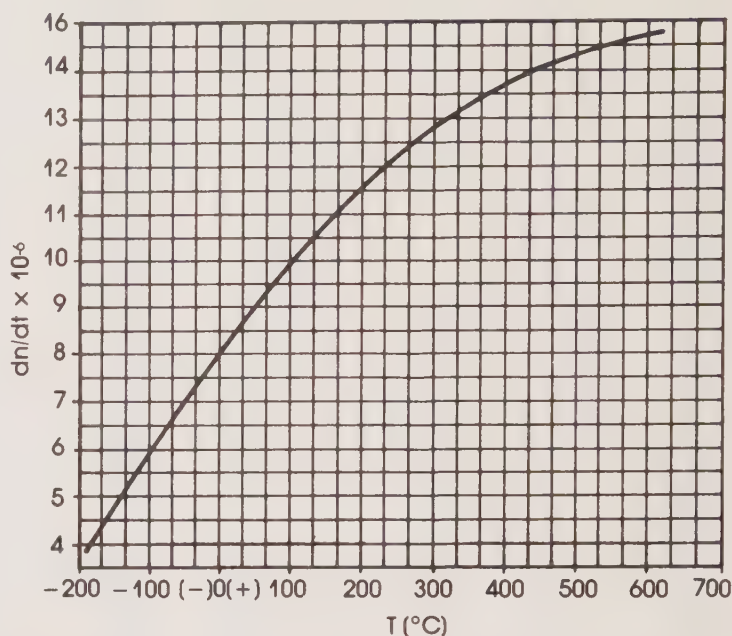
$$\frac{\Delta n}{\Delta T} (20^\circ\text{C to } 30^\circ\text{C})$$

at 0.2100 micrometers	15×10^{-6}
.3650	10.7
.4047	10.1
.5461	9.9
.5876	9.9
.6328	9.9
.6563	9.9
2.0	12
3.7	10

Birefringence Constant: $3.46 \mu\text{m cm}^{-1} / \text{kg cm}^{-2}$ Dispersion equation at 20°C

$$n^2 - 1 = \frac{0.6961663\lambda^2}{\lambda^2 - (0.0684043)^2} + \frac{0.4079426\lambda^2}{\lambda^2 - (0.1162414)^2} + \frac{0.8974794\lambda^2}{\lambda^2 - (9.896161)^2}$$

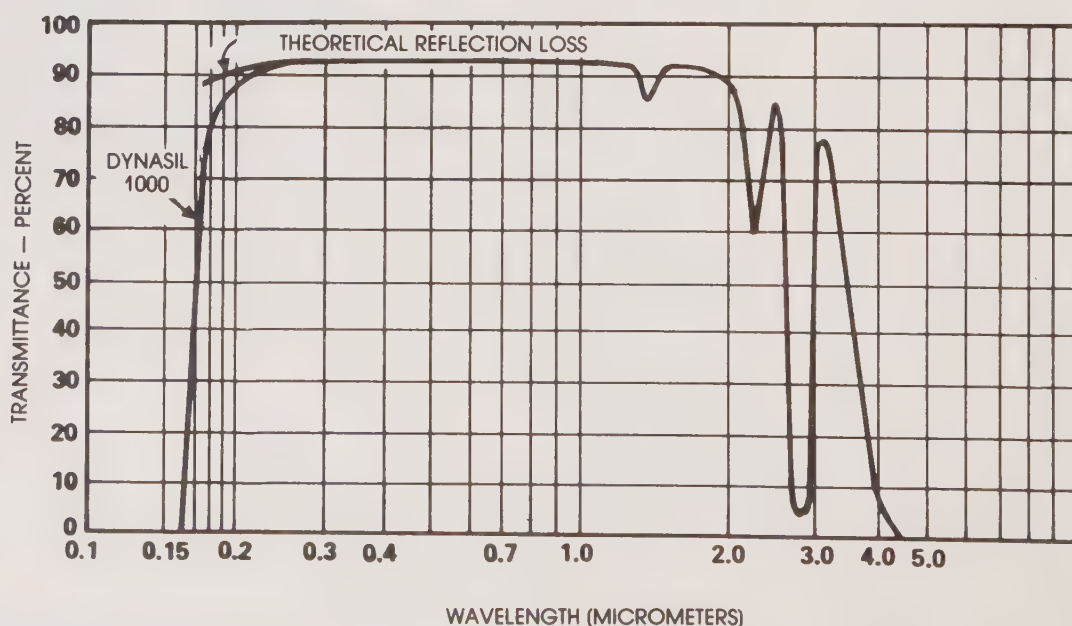
Refractive Index

Change with Temperature ($\lambda = 587.6 \mu\text{m}$)

SOURCE: DYNASIL CORPORATION

Typical Transmittance of Fused Silica

Transmittance (10mm Thickness — Reflective Losses Included)



SOURCE: DYNASIL CORPORATION

Optical Plastics: Properties and Tolerances

PLASTIC FABRICATION TECHNIQUES

Production volume is one important factor for determining the practicality of molded plastic optics. If the anticipated volume is only a few dozen lens elements, conventional glass production techniques are the least expensive. When the quantity is from several hundred up to one or two thousand lenses, high-speed glass grinding and polishing techniques are competitive. In quantities from one or two thousand upward, molded plastic optics have been supplied when the quality, weight and/or other factors warrant their consideration.

Common manufacturing techniques for plastic optics include casting, molding or machining.

Casting

Casting is generally employed for unusually large optical components or for prototype applications. An exception to this is in the ophthalmic industry. In this application spectacle lenses are cast usually with one face finished, and the other face is left for custom grinding and polishing. A thermosetting compound CR-39 (allyl diglycol carbonate, or ADC; CR-39 is a product of Pittsburgh Plate Glass) is almost exclusively used for this application.

Glass molds are usually employed, and the curing cycle must be conducted under carefully controlled temperature conditions to avoid the introduction of strains and distortion. To achieve significant production throughput a large number of molds are required, and that increases production costs. It is generally agreed that compensation for material shrinkage cannot adequately be controlled during the cooling cycle to obtain diffraction-limited optics. Shrinkage for this material is one of the highest (i.e., up to 14%) and its change in index of refraction with temperature is also high ($dn/dt = 14.3 \times 10^{-5}/^{\circ}\text{C}$).²

Molding

Two molding techniques are used in high volume production: compression and injection molding. In compression molding, plastic is introduced in either powder or sheet form. The material to be molded is pressed between heated dies in a vertical flatbed press. Since the dies generally have to be temperature-cycled during

each pressing, the cycle time is relatively long, that is, from 5 to 20 minutes per cycle. The dies are generally made by electroforming. Multiple impressions from a single die are possible, and several dies may be pressed at one time by one machine, so that the machine time per part can be quite acceptable.²

The compression molding process has been developed to a fine art by the phonograph record industry which routinely reproduces detail smaller than optical wavelengths in high volume. In the optical industry the process has been utilized mainly for the production of Fresnel lenses and lenticular lens arrays, where detail rather than quality is important.

The majority of high-quality plastic optics fabricated in volume are made by injection molding. In this process, the molding powder is liquefied by heat and is injected into a temperature-controlled mold at high pressure (up to 10,000 psi). The plastic solidifies in the mold before being removed. Cycle times for this process are typically $\frac{1}{2}$ minute for smaller components up to 3 or 4 minutes for larger components.³

The tooling mold for this process consists of a steel mold base and optically polished chromium stainless-steel inserts. Depending upon the part size and component quality desired, the tooling mold can be configured as a multiple cavity mold to produce several components from one injection.³

Virtually all the tooling for plastic optics is in the mold; hence, virtually all the cost in plastic optics is in the mold. The mold consists of a steel mold base containing the cooling passages, the sprue bushing to mate with the injection nozzle and various movable plates to actuate ejector pins, etc. The actual cavity used to form the component consists of two parts: receivers, containing nonoptical details of the part, and polished inserts defining the optical surface. Most manufacturers utilize 420F or 440C hardenable chromium stainless steel for both the receivers and inserts. Conventional glass grinding and polishing techniques or single-point diamond machining are employed to fabricate the inserts to light wavelength tolerances. Final shaping in both cases is obtained by manual polishing.

Almost everyone (i.e., both glass and plastic engineers) agrees that

the tooling mold design is highly specialized. Given the correct design, the mold can accommodate and integrate mounting flanges, spaces, holes, staking tenons, etc., into the optical part, thereby simplifying assembly and often eliminating other costly components and operations. Multiple cavity production can reduce the cost of the component somewhat; however, consideration must be given to optical quality. When high-quality plastic components are desired, more careful control over the complete process can be obtained with a single cavity or a limited number of cavities. Location of the injection gate and the size of the gate, in addition to controlling the injection pressure and temperature, are important for high optical quality. When variances in the molding process need be held closely, then it is sometimes necessary to revert to in-line injection process control with the aid of sensors and electronic feedback. This level of sophistication, rarely employed, has been implemented for precision work.^{3,4}

Materials

The materials available for plastic optics are limited as compared to the selection available in glass. This is best illustrated by a "glass map" (see Figure 1). The large open circles represent the available plastic types utilized in designing precision plastic optical systems. As one can see, plastics are confined to the region bounded by an index of $n_d < 1.6$ and Abbe numbers $V_d < 60$.

Plastic optical materials available are classified as either thermoplastics or thermosets. Thermoplastics can be resoftened repeatedly without undergoing any change in chemical composition. The word thermoplastic literally means "heat-flowable," yet some thermoplastics do not flow under heat, and some flow without heat under mechanical pressure only.

Thermosets, on the other hand, means "heat sets," yet some thermosets can be set without heat. Actually the main distinguishing feature between the two classes is whether the polymer chain remains linear and separate after molding or whether it undergoes a three-dimensional chain-combination cross-linking. Linear plastics are chemically unchanged during molding and can be remolded again and again. Cross-linked plastics' linear chains are joined irrevers-

ibly during molding into an interconnected molecular network and cannot be remolded.

Cross-linking can be initiated by heat, chemical agents, irradiation or a combination of these. To avoid confusion between terms, that is, thermoplastic and thermoset, the more generalized terms "linear" and "cross-linked" can be substituted. That is, thermoplastic is called "linear," and thermoset "cross-linked." Some of the more important optical and thermal parameters of thermoplastics and thermosets are listed in Table 1.

The index of refraction of usable plastics ranges from approximately 1.45 to 1.60. Some fluoropolymers have indices down to 1.34, but in thicknesses greater than 0.002 inch such materials are translucent. Laboratory samples of polycarbonates have been produced with indices up to 1.66, but nothing close to that is commercially available.

Plastic producers can maintain uniformity of refractive index from run to run within ± 0.0005 , almost as good as can be obtained in optical glass. When uniformity is in doubt or when higher control is required, components to be manufactured should be taken from one production batch.

The variations of refractive index in a lens due to inhomogeneities of the material affect the element's ability to focus an image. Glass in random size and cut blanks as obtained from Schott Glass Technologies has an optical homogeneity that is guaranteed not to exceed $\pm 1 \times 10^{-4}$. The area of the inhomogeneity is on the order of 3×10^{-6} cm (i.e., 300A or 1.2×10^{-6} inch).

In special orders glass can be obtained whose maximum variation in the n_d value is $\pm 1 \times 10^{-6}$ (i.e., H4 homogeneity group). Tests with acrylic lenses reveal refractive index variations of 1.7×10^{-4} and inhomogeneities with the long dimension on the order of 3×10^{-5} cm (i.e., 3000 A or 1.2×10^{-5} inch).¹ The Abbe value V_d is defined as:

$$V_d = \frac{n_d - 1}{n_f - n_c}$$

The index difference $n_f - n_c$ is called the main dispersion. The wavelengths at which the index of refraction is measured are:

$$\begin{aligned} n_d & \lambda = 589.3 \text{ nm} \\ n_f & \lambda = 486.1 \text{ nm} \\ n_c & \lambda = 656.3 \text{ nm} \end{aligned}$$

Traditionally glasses with $n_d > 1.60$, $V_d > 50$ and $n_d < 1.6$, $V_d > 55$ are designated as crowns, and the remaining types classified as flints. A material with a higher Abbe number will have

less color separation. As with most optical materials, the lower-index plastics have the higher Abbe values.

The variation in refractive index with temperature dn/dt can range from 6 to 50 times greater than that of glass depending upon the specific materials being compared. For acrylic the change in index of refraction with temperature is approximately $-8.5 \times 10^{-5}/^\circ\text{C}$, and for BK 7 glass the value is $+0.3 \times 10^{-5}/^\circ\text{C}$.

Plastics as well as glasses in bulk form retain residual strains even after annealing. Working the part in conventional machining and polishing techniques can also induce additional stresses. The stresses developed when a plastic is injection-molded hot and cooled rapidly can be large. These stresses will cause the plastic to have two indices of refraction, one in the direction of flow and the other across the flow, a condition known as birefringence. This stress-induced refractive index variation is in the area of 0.06×10^{-3} for acrylic and as high as 8×10^{-3} for polystyrene.

Birefringence is specified in nm/cm (thickness). For optical systems with extremely high performance, low birefringence is extremely important. The development of special annealing methods permits the plastic or glass blank to achieve very small residual strain (i.e., low birefringence).

The heat annealing in glass may reduce the birefringence to 3 to 4 nm/cm (super-special precision annealing). Glass blanks with diameters up to

300mm can be guaranteed with a stress birefringence $\leq 10 \text{ nm/cm}$ (normal quality) and $\leq 6 \text{ nm/cm}$ (normal quality with special annealing or precision quality).

The thermal expansion of plastic is higher than that of glass. For example, the coefficient of linear thermal expansion for acrylic is $7 \times 10^{-5} \text{ cm/cm}/^\circ\text{C}$ while that for common crown glass is $0.7 \times 10^{-5} \text{ cm/cm}/^\circ\text{C}$.

Haze is the amount of stray light scattered within an element due to surface imperfections or embedded particles. For optical plastic only one surface imperfection between 0.004 in. and 0.010 in. is permitted per square foot. Standard plastic elements must be free of bubbles and foreign particles larger than 0.002 in. Only one embedded particle with an average diameter of less than 0.0008 in. is permitted per 20cc of material.

MATERIALS

Acrylic (Polymethyl methacrylate)

Acrylic, by far the most widely used plastic, is the "crown" of plastics. Acrylic has a refractive index of $n_d = 1.491$. The change in index with temperature dn/dt is $8.5 \times 10^{-5}/^\circ\text{C}$ between 20°C and 40°C . The index of refraction as a function of wavelength and as a function of temperature is shown in Figures 2 and 3 respectively. Acrylic is readily moldable, has good stability and is the easiest of the popular optical plastic materials to machine and polish. It has a low thermal conductivity, which reduces heat dissipa-

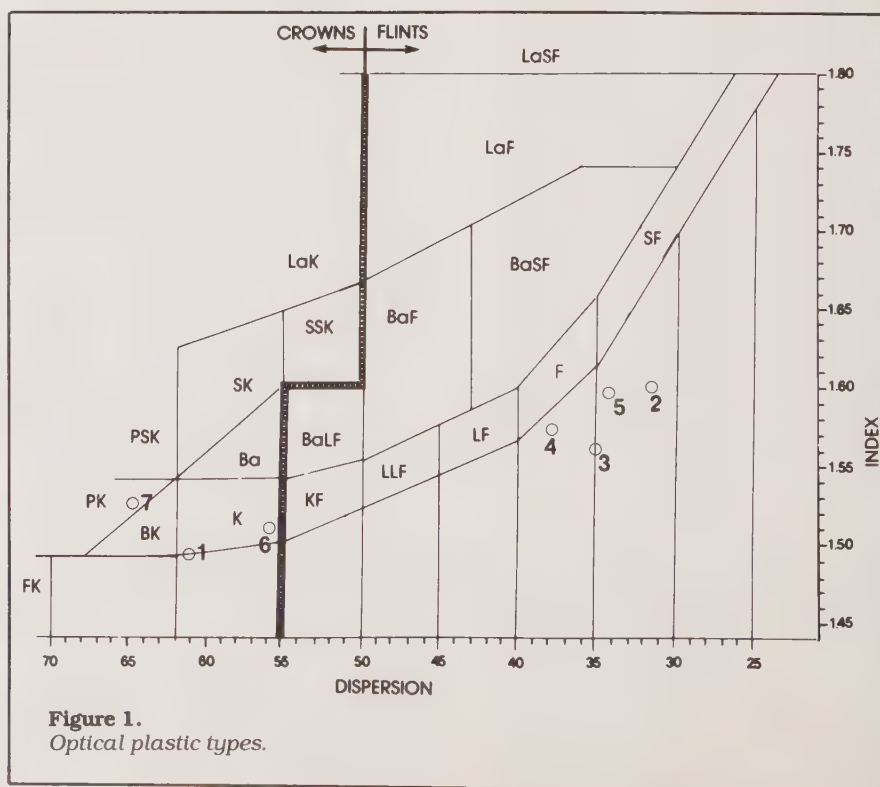


Figure 1.
Optical plastic types.

tion, and therefore a lubricant such as water must be used in machining. Water absorption has some effects on the optical properties of acrylic. Samples immersed in water for 10 days at 23°C (73°F) show a 0.2% increase in linear dimensions.

The linear thermal expansion of acrylic is 8 to 10 times larger than glass. For example, a 25mm (1 in.) diameter lens will change 0.0762mm (0.003 in.) when heated from 27°C (80°F) to 65°C (150°F), and the focal length of 50mm (2 in.) will increase only 0.2mm (0.008 in.) over this temperature range.¹ The coefficient of linear expansion for acrylic is approximately 7.0×10^{-5} cm/cm/°C.

On the other hand, the optical memory (i.e., the return of a part to its original dimensions) of acrylic after cooling from an elevated temperature is better than glass. The shrinkage at elevated temperatures for an acrylic bar 6.35mm $\times$ 241.3mm (0.25 $\times$ 9.5 inches) after 48 hours varies from 0.1% (70°C), 0.1% (80°C), 0.3% (90°C), 0.5% (100°C) to 6% (110°C). Shrinkage from cold-mold dimensions to a cold piece over 48 hours (Shrinkage Test ASTM, Test Method D1299-55) amounts to 0.0508mm (0.002 inch) to

0.1524mm (0.006 inch) per 25.4mm, that is from 0.2% to 0.6%.

Acrylic is highly transmissive (i.e., approximately 92%) and has very little internal scattering that contributes to haze. Acrylic materials have been developed that are transmissive in the ultraviolet, and the material holds up well for years without perceptible aging. The transmission of standard acrylic, a UV-grade acrylic, polystyrene and a polycarbonate are shown in Figure 4.

Polystyrene

Polystyrene, the "flint" of plastics, has a refractive index of $n_d = 1.590$. When a styrene element is combined with an acrylic element to make an achromatic lens corrected for the f and c lines, the secondary spectrum (i.e., the difference between f and d lines) can generally be more completely corrected than can be accomplished with a glass achromat.

Early polystyrene had impurities that decreased the light transmission in the blue end of the spectrum and caused the polymer to have a yellowish tint. In currently available blanks this is visible only in thick sections. The overall luminous trans-

mission of 88% is somewhat lower than for acrylic (92%). The material is easily injection-molded; it is stable in molding but unstable in transmission when exposed to near ultraviolet.

Copolymers of Styrene and Acrylic: NAS (Methyl methacrylate)

A copolymer of styrene and acrylic, methyl methacrylate styrene (NAS) is made up of 30% styrene and 70% acrylic. The index of refraction is listed varying from $n_d = 1.533$ to 1.567 depending upon the blend. The distortion temperature is comparable to acrylic.

SAN (Styrene acrylonitrile)

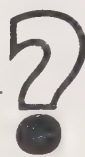
SAN is another copolymer of styrene having a high refractive index, $n_d = 1.567$, and a low thermal expansion coefficient. SAN can be used in place of styrene; it molds well and is quite stable, but tends to yellow.

Polycarbonate

Polycarbonate is an extremely tough optical plastic. Its high impact strength, although not important for most precision optical applications, is desirable in streetlight

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lenses, construction warning lights, automotive tail lights, and other applications requiring durability and ruggedness. In these outdoor applications ultraviolet stabilizers can be added to the compound with only a 5% loss in visible transmittance.

Another advantage of polycarbonate is its performance over a broad range of temperatures, from -137°C (-215°F) to 121°C (250°F). Heating the material to 104°C (220°F) results in an increase in linear dimensions of only 0.07%.

Polycarbonate is not easily machined because of its high ductility; therefore its use is confined to injection molding, although its molding properties are not as good as those of acrylic or styrene. The material scratches more easily, its light transmission is less than acrylic, and its cost is significantly higher than either acrylic or styrene. Its index, $n_d = 1.586$, is close to styrene; however, other types, not commercially available, have been formulated with indexes ranging from 1.560 to 1.654.

TPX (Methylpentene)

Methylpentene is a thermal plastic sold under the tradename TPX by ICI America. It is a lightweight plastic that is very tough and has better electrical properties than any other transparent plastic. It is unaffected by a great many different chemicals even up to 160°C (320°F). But a major disadvantage to this plastic is

that it shrinks from 0.15 to 0.30 cm/cm during molding.

ABS

ABS resins are terpolymers of acrylonitrile, butadiene and styrene. Its light transmission in comparison to acrylic is poor, being approximately 80% for a thickness of 6.35mm. It is tougher than most other optical plastics and costs less than polycarbonates. There are several other thermoplastics available, including polysulfane, cellulose, vinyls, CTFE fluoropolymers, polyester copolymers and ionomers, but these materials are seldom used in optical systems.

CR 39

There is only one important optical thermoset (cross-linked) plastic: allyl diglycol carbonate (ADC), commonly known as CR 39. It is widely utilized in the ophthalmic industry to fabricate cast plastic eyeglass lenses. ADC has excellent optical clarity and good resistance to abrasion, impact and chemicals. It can withstand continuous temperatures up to 100°C and short-term temperatures to about 150°C. Its high shrinkage (i.e., up to 14% during casting) limits its use. ADC is quite expensive, and the casting process too is considerably more expensive than injection molding.

There are other thermosets available in optical grades, including epoxies, silicones, urethanes and cross-linked acrylics. These materials are

seldom used as optical elements themselves but are utilized as add-ons to aspherize a surface.

MANUFACTURING AND PRODUCTION TOLERANCES

The listing of plastic lens fabricators is quite extensive, and as in any industry, a knowledge of each manufacturer's capabilities is extremely important. The following factors may be significant in selecting a vendor for a particular job:

- Is the tooling designed and fabricated in-house or farmed out?
- What lens element shapes does the manufacturer have experience in working with? Spheres, cylindrical, toroidal, parabolic, aspheres, flats, etc?
- What materials has the manufacturer worked with?
- What fabrication techniques does the manufacturer employ? Machining, compression molding, injection molding, etc.?
- What is the production volume capability of the manufacturer?
- What coating experience does the manufacturer have, and does he do the coating in-house?
- What testing facilities does the manufacturer have: Mold insert testing, finished component testing, environmental, etc?
- What optical and mechanical tolerances does the manufacturer work to?

Confining manufacturing tech-

TABLE 1.
PROPERTIES OF PRINCIPAL OPTICAL PLASTICS

	Acrylic	Styrene	NAS	SAN	Polycarbonate	TPX	ABS	ADC	Glass
Units	Polymethyl Methacrylate (Lucite) (Plexiglass)	Polystyrene (Dylene) (Styron) (Lustrex)	Methyl Methacrylate Styrene Copolymer	Styrene Acrylonitrile (Lustran) (Tyril)	(Lexan) (Merlon)	Methylpentene (TPX)		Allyl Diglycol Carbonate (CR 39)	BK 7
Refractive Index, n									
$n_d(589.3\text{nm})$	1.491	1.590	1.533-1.567	1.567-1.571	1.586	1.467	1.538	1.504	1.517
$n_c(656.3\text{nm})$	1.488	1.585	1.558	1.563	1.581	1.464		1.501	1.514
$n_f(486.1\text{nm})$	1.496	1.604	1.575	1.578	1.598	1.505		1.510	1.522
Abbe Value, V_d	61.4	31.1	35	37.8	34.5	11.4		56	64.6
Rate of Change in Index									
with Temperature	$dn/dt \times 10^{-5}/^\circ\text{C}$	-8.5	-12.0	-14.0	-11.8 to -14.3			-14.3	+0.3
Coefficient of Linear Expansion	$\text{cm/cm} \times 10^{-5}/^\circ\text{C}$	6.74 @ 70°C	6.0-8.0		6.5-6.7	6.6-7.0	0.83	11.4	0.71
								25 to 75°C	
								14.4	
								75 to 125°C	
Deflection Temperature									
3.6°F/min. 264 psi	°C	92	82		99-104	142	90		
3.6°F/min. 66 psi	°C	101	110	100		146	84		
Recommended Max. Cont. Service Temp.	°C	92	82	93	79-88	124		100	
Thermal Conductivity	$\text{cal/sec-cm}^\circ\text{C} \times 10^{-4}$	4.96	2.4-3.3	4.5	2.9	4.65	4.0	5	0.266
Haze	%	2	3	3	3	3	5	12	3
Luminous Transmittance	% Thickness	92	88	90	88	89	90	79-90.6*	93
	3.175mm								99.9
Water Absorption	% Immersed	0.3	0.2	0.15	0.2-0.35	0.15		0.2	
	24 hr @ 23°C								
Mold Shrinkage	%	0.2-0.6	0.2-0.6	0.2	0.2-0.6	0.5-0.7	1.5-3.0		

* Luminous Transmittance 79%, thickness 6.35mm; 90.6%, thickness 0.381mm

See References 1, 3, 4, 5, 6, 7, and 8.

niques to injection molding for refractive plastic components of high quality, some general tolerances can be established. As in any manufacturing process (i.e., glass optics or plastic optics), the tolerances depend upon some or all of the following:⁹

- Type of material;
- Component type (i.e., spherical-positive or negative, cylindrical, toroidal, flat, aspheric, etc.);
- Lens element size;
- Element aspect ratio (i.e., vertex-to-edge thickness, length to thickness, etc.);
- Cost (i.e., tooling cost and/or production cycle time);
- Environmental conditions;
- Application (i.e., condenser quality, imaging quality, etc.);
- Production volume; and
- Lens manufacturers' capabilities, experience & ingenuity.

Tolerances have been established for injection-molded lenses and are listed in Table 2. The tolerance limits should only be taken as guidelines.

Thermal considerations

Most of the thermal properties of plastics have been considered in the preceding discussion and are listed in Table 1. Thermal parameters listed include rate of change of refractive index with temperature, coefficient of linear expansion, birefringence, deflection temperatures, maximum continuous service temperature and material thermal conductivity.

The maximum recommended continuous service temperature for plastics is approximately 80°C to 120°C and depends on the specific material. Deflection temperatures are typically listed for a 3.6°F-per-minute rate at pressures of either 264psi or 66psi. Deflection temperatures typically range from 80°C to approximately 145°C.

When molding a lens, both the material's linear coefficient of expansion and birefringent properties are important. Stresses will develop when a plastic is injection-molded hot and cooled rapidly. The results of birefringence can be visually observed through inspection with a polariscope. Stresses will also develop with improper gating of the mold insert and in areas where flanges or the like are added. As noted before, these stresses will cause the plastic to exhibit birefringence. Polystyrene may have a stress-induced birefringence as high as 8×10^{-3} while acrylic will be in the area of 0.06×10^{-3} . But proper mold design and careful control over the injection-molding process are usually sufficient so that birefringence does not present a problem.

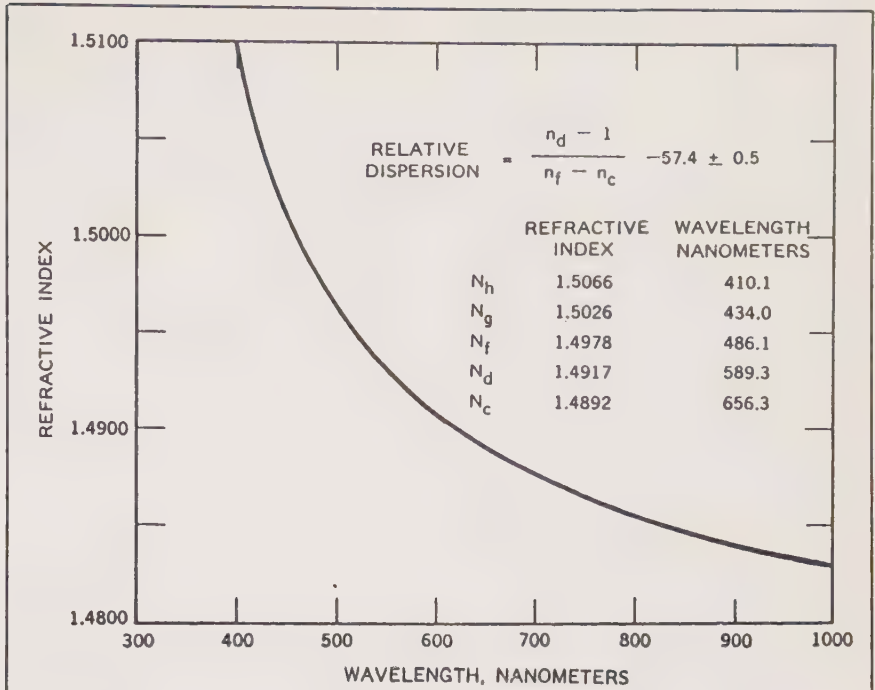


Figure 2.
Refractive index of polymethyl methacrylate.

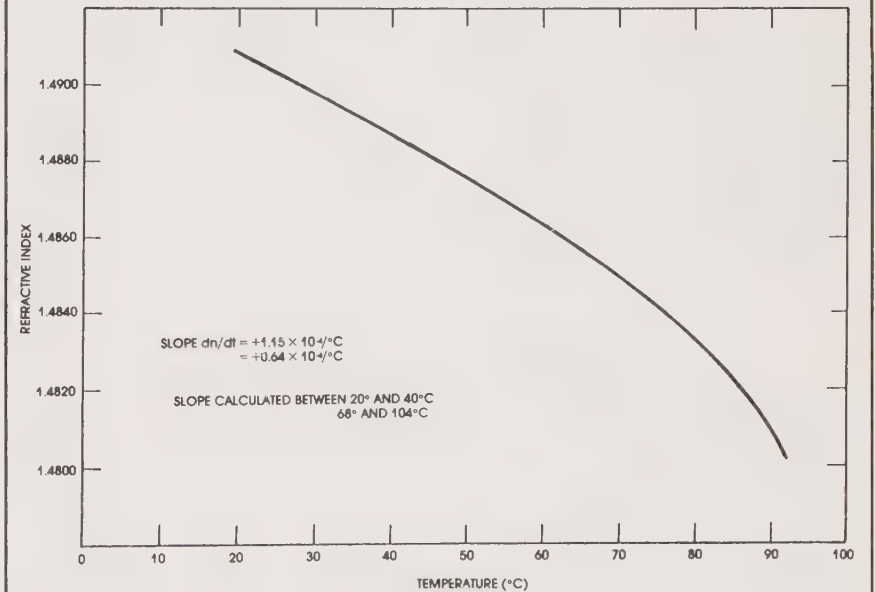


Figure 3.
Refractive index vs. temperature for polymethyl methacrylate.

A material's linear coefficient of expansion and contraction is usually more important in mold design to ensure that the finished component has the correct optical and mechanical dimensions. The change of a component's dimensions with temperature after fabrication—that is, radii and thickness—are usually second-order effects. For example, an acrylic lens 25.4mm (1 inch) in diameter will change 0.0762mm (0.003 in.) when

heated from 27°C (80°F) to 65°C (150°F), and if the focal length is 50mm (2 inches) it will increase by 0.2mm (0.008 in.) over this temperature range.¹

Depending upon the particular material and production process employed, shrinkage of a typical molded plastic component is usually between 0.1% and 0.6% of the dimensions of the mold. To minimize this problem the edge-to-vertex thickness should

be kept as uniform as possible. For this reason, molded elements with edge-to-vertex thicknesses less than 2:1 are generally easy to mold, less than 3:1 moderately difficult and less than 4:1 difficult. In addition to controlling production cycle times and temperatures, some success can be gained by compensating for this shrinkage in the mold. This is usually an iterative process that is aided if the manufacturer has diamond-turning machine capabilities with computer-controlled correction for the mold inserts.

Aside from achromatization, the change in index of refraction with temperature is the most important parameter to control. The variation in index with temperature dn/dt can be from 6 to 50 times greater than that of glass depending upon the specific materials being compared. For acrylic the change in refractive index with temperature is approximately 30 times greater than for BK 7 glass and of opposite sign (i.e., $-8.5 \times 10^{-5}/^{\circ}\text{C}$ vs. $+0.3 \times 10^{-5}/^{\circ}\text{C}$).

Coatings

In general, coatings that are applied to glass elements can also be applied to plastics. These include reflectors, partial reflectors, antireflection coatings, antistatic and abrasion-resistant coatings. The deposition process on glass is usually conducted at substrate temperatures of 200-300°C at 10^{-5} torr vacuums.

Plastic materials may contain moisture, solvents or plasticizers in varying amounts that are released in a vacuum. One method of overcoming this outgassing is to provide a higher pumping speed relative to the outgassing area. This works to a certain extent, but can leave the surface pitted. In most cases it is therefore necessary to deposit at lower pressures as well as lower temperatures, and these factors lead to poorer adhesion on plastic. This need not be a detriment in an optical system if the surfaces coated can be adequately protected. As technology progress-

es many of the environmental problems may be overcome, and some evidence of this exists today. There are some coating suppliers that advertise plastic coatings that will meet the adherence, hardness and humidity specifications of MIL-M-13508.

Reflective coatings

Reflective coatings on plastic have long been utilized for decoration, reflectors and the like. When surface quality is not important, base coats of thermosetting lacquers are first applied to the plastic substrate to seal the surface and to provide a

TABLE 2.
INJECTION MOLDING TOLERANCES

	Low Cost	Commercial	Precision
Focal Length	$\pm 3\%/5\%$	$\pm 2\%/3\%$	$\pm 0.5\%/1\%$
Radius of Curvature	$\pm 3\%/5\%$	$\pm 2\%/3\%$	$\pm 0.5\%/1\%$
Figure - Spherical	10 to 30 f	5 to 10 f	2 to 5 f
Figure - Flat	---	---	---
Irregularity	3 to 7 f	1 to 3 f	1 to $\frac{1}{2}$ f
Surface Quality	80/50	60/40	40/20
Centration	$\pm 3\text{min}$	$\pm 2\text{min}$	$\pm 1\text{min}$
Vertex Thickness (in.)	± 0.010	± 0.007	± 0.003
	± 0.015	± 0.004	± 0.002
Diameter or Length (in.)	± 0.010	± 0.007	± 0.003
	± 0.015	± 0.004	± 0.002
Repeatability Tolerances	1% to 2%	0.5% to 1%	0.3% to 0.5%
Lens-to-Lens			

Note: Tolerances given in optical fringes abbreviated by "f."

Vertex-to-Edge Thickness Ratio

- 4:1 Difficult to mold
- 3:1 Moderately easy to mold
- 2:1 Easy to mold

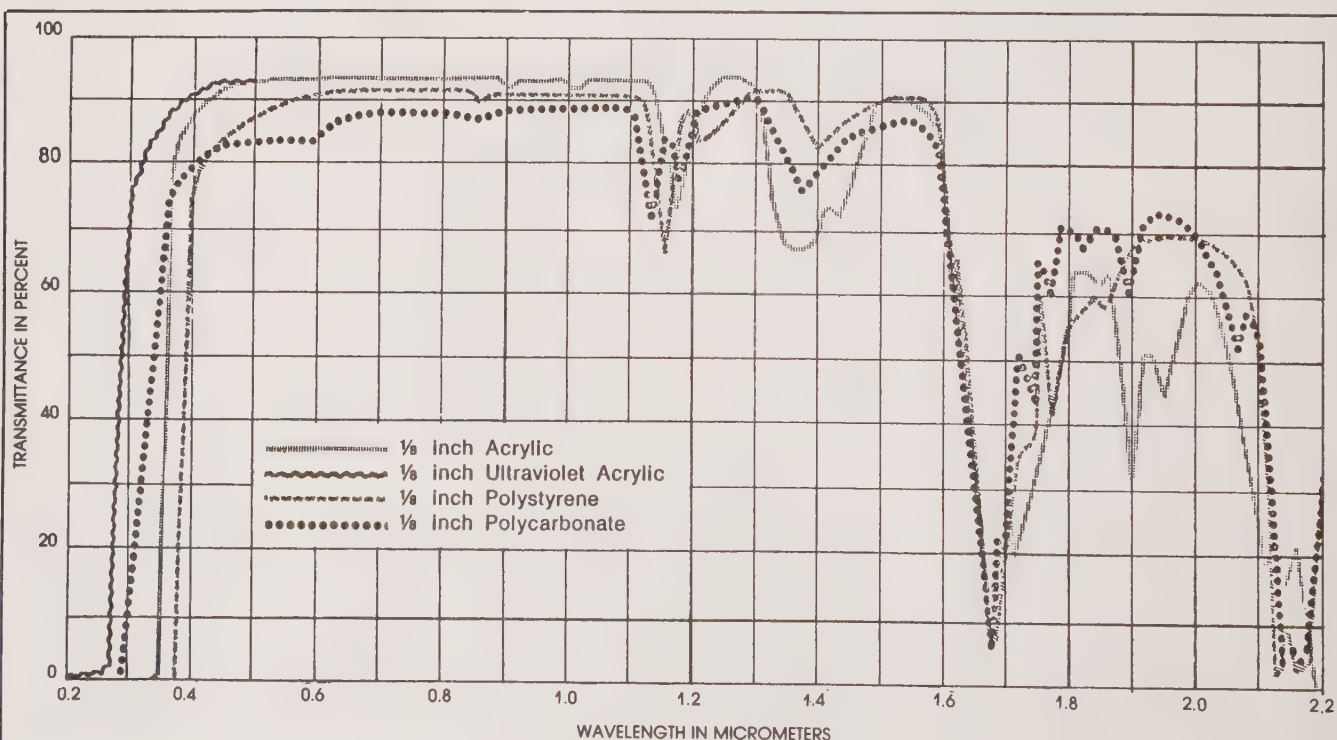


Figure 4.
Transmission characteristics of principal optical plastics.

smooth glossy surface to which a subsequent metal film can adhere. For most optical applications other than condenser-quality elements, coating requirements are more critical, such as those for producing the thickness control and surface purity required in high-quality mirrors. In these cases vacuum deposition of an adherence and sealing layer may be done prior to the reflective coating. Reflectance coatings of aluminum, silver and dielectric layers have been successfully applied. More durable reflective coatings can be obtained through replication. In this instance a hard durable coating is vacuum-deposited on a master tool and then transferred to the plastic substrate.

Antireflection coatings

Of the 8% transmission loss in acrylic, 7.5% is due to surface reflections; in polystyrene reflection causes a 10.6% loss. These losses occur with all transparent materials where air is the adjacent medium. For a multiple lens system, surface reflectivity losses can be a serious problem from the standpoints of both low throughput efficiency and veiling glare. For example, an air-spaced triplet having two acrylic elements and one polystyrene element has a total transmission loss due to reflection on the order of 25%.

Magnesium fluoride (MgF_2) with an index of $n_d = 1.38$ in thin film form is widely utilized for a single $\frac{1}{4}\lambda$ coating on acrylic and polystyrene. A single element of two surfaces, when properly coated, will have reflection losses reduced from 8% to 3% at 460nm, 2.5% at 530nm, 2.5% at 570nm and 3% at 600nm.

Both "V" coats and broadband antireflection coatings are also available for plastics. As with any manufacturer, the coating vendors also have proprietary techniques. The durability and environmental quality of these coatings are highly variable, just as are the materials upon which they can be successfully deposited. An example of the efficiency that can be obtained with "V" coats and broad-band coatings is shown in Figure 5.

Antistatic coatings

Nonconductors such as plastics have high surface resistivity and cannot only readily acquire an electrostatic charge, but they retain a charge almost indefinitely. Liquid household detergents can provide temporary protection from static charge, but commercial destaticizers are necessary for longer-lasting effects.

Vacuum-deposited coatings are also available as destaticizers. Ameri-

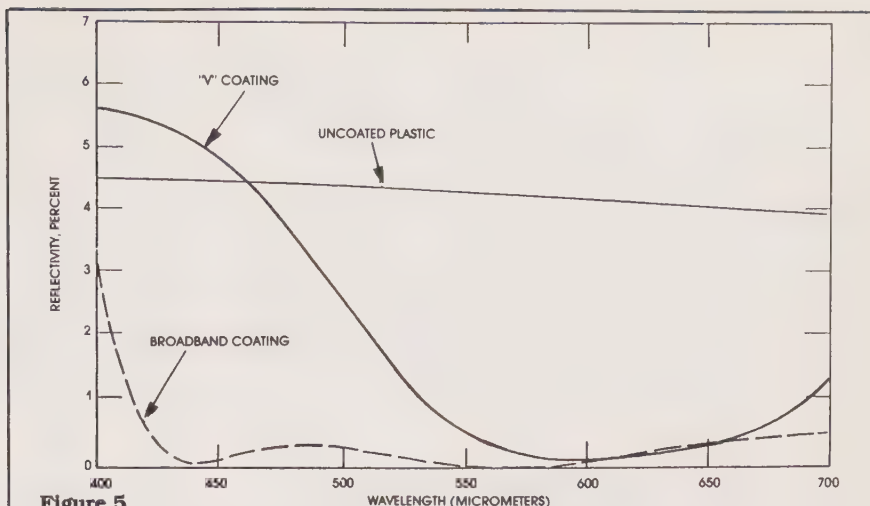


Figure 5.

Comparison of uncoated plastic with those bearing "V" coats and broad-band coatings.

can Optical Corporation has perfected a coating that combines antistatic properties with antireflection properties. This coating, AO-50m, deposited on polystyrene, reduces reflection losses from approximately 10.6% to 4% at 550nm. Its abrasion resistance and environmental qualities also offer improvements.

Abrasion-resistant coatings

In some applications where only the abrasion-resistant qualities of a plastic substrate need to be improved, certain specially developed coatings have been applied. Until recently these coatings have been suitable only for polycarbonate because of high curing temperatures. This has changed recently, and new coatings are available, including Dupont Abcite, American Optical AO-50M, and coatings by Mobay Chemical, Owens-Illinois and 3M.

Cleaning

As you might imagine, plastic elements cannot be subjected to the same cleaning agents as glass. For example, acetone or alcohol will cause the surface of most plastics to craze. Some of the techniques and precautions for cleaning are universal, in general:

- Do not handle the coated surface;
- Use a stream of dry air, nitrogen, etc., to blow particulate contaminants from the optical surfaces;
- For organic contaminants use a stream of suitable solvent followed by forced air, nitrogen, etc., dry;
- Stubborn organic contaminants may be removed by cleaning in an ultrasound bath for a short duration, followed by vapor degreasing in a suitable solvent.

Suitable solvents that have been employed are:¹⁰

• Acrylic: Solvent stream - Leptane, freon TF; Ultrasound - freon TF, liquid detergent in di- H_2O ; Vapor degrease-freon TF.

• Styrene: Solvent stream - ethyl alcohol; Ultrasound - freon TF, liquid detergent in di- H_2O ; Vapor degrease-freon TF.

If possible, it is always best to avoid cleaning; but if cleaning is unavoidable, it is wise to check for chemical attack on a small surface prior to a large-scale wash. The almost unobtainable cleaning axiom is: Avoid abrasive contact and pick a solvent that does not attack the substrate or coating and leaves no residue upon drying.

H.D. Wolpert

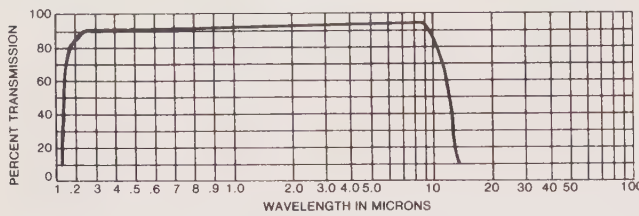
Loral Electro-Optical Systems

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Optical Materials: Transmission and Refractive Index

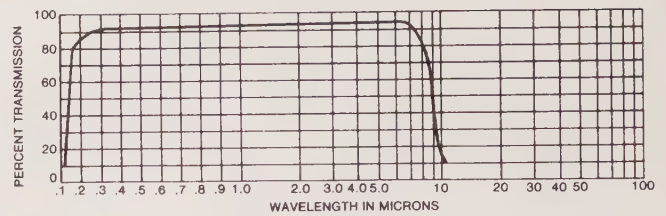
Barium Fluoride (BaF₂)



Barium Fluoride Refractive Index vs. Wavelength

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
0.26	1.51	0.85	1.47	8.00	1.43
0.30	1.50	3.24	1.46	8.60	1.42
0.36	1.49	5.14	1.45	9.20	1.41
0.48	1.48	6.50	1.44	9.80	1.40
				10.6	1.39

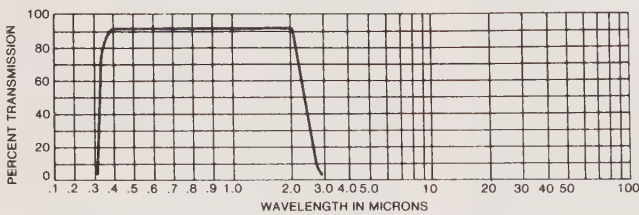
Calcium Fluoride (CaF₂)



Calcium Fluoride Refractive Index vs. Wavelength

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
0.19	1.51	0.33	1.45	5.80	1.39
0.20	1.50	0.41	1.44	6.20	1.38
0.21	1.49	0.88	1.43	6.70	1.37
0.22	1.48	2.65	1.42	7.00	1.36
0.25	1.47	3.90	1.41	7.50	1.35
0.27	1.46	5.00	1.40	8.22	1.34

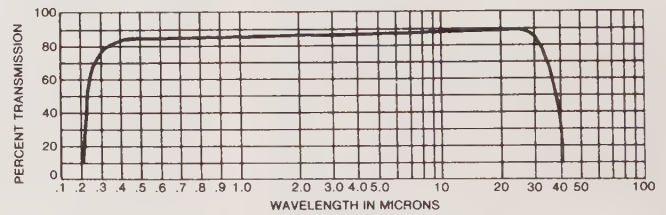
Borosilicate Crown Glass (BK7)



BK-7 Glass Refractive Index vs. Wavelength

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
0.37	1.535	0.63	1.515	2.00	1.495
0.40	1.530	0.84	1.510	2.30	1.490
0.43	1.525	1.06	1.505	2.60	1.485
0.52	1.520	1.60	1.500		

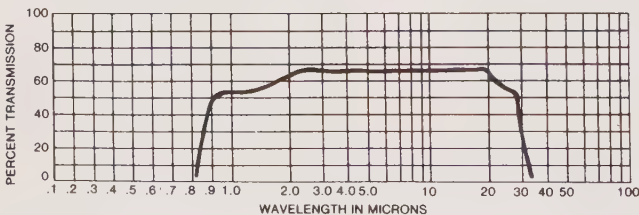
Cesium Bromide (CsBr)



Cesium Bromide Refractive Index vs. Wavelength

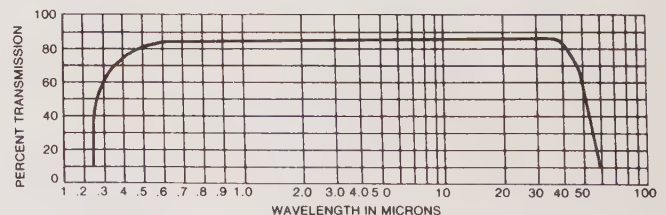
$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
0.45	1.72	11.8	1.66	32.1	1.60
0.51	1.70	21.3	1.64	36.0	1.58
0.91	1.68	27.4	1.62	39.3	1.56

Cadmium Telluride (CdTe)



$n = 2.67$ at $10.6\mu\text{m}$

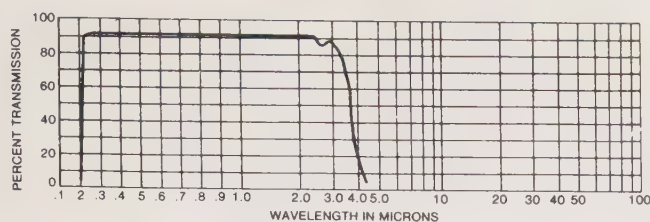
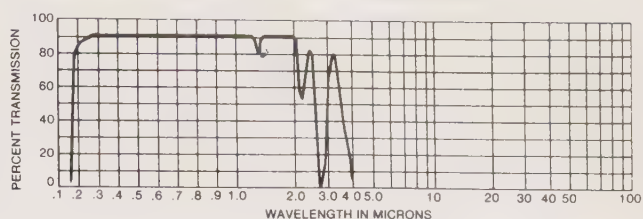
Cesium Iodide (CsI)



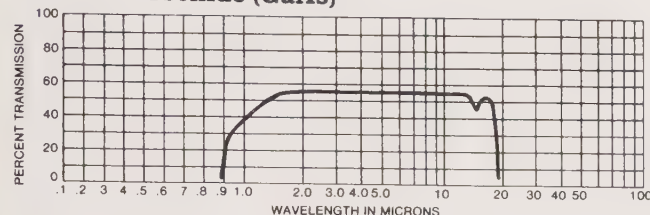
Cesium Iodide Refractive Index vs. Wavelength

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
0.29	1.98	0.39	1.86	9.00	1.74
0.31	1.96	0.42	1.84	24.4	1.72
0.32	1.94	0.46	1.82	33.0	1.70
0.33	1.92	0.52	1.80	39.5	1.68
0.35	1.90	0.64	1.78	44.7	1.66
0.37	1.88	0.92	1.76	49.3	1.64

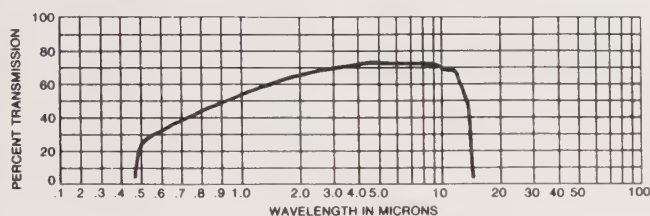
Source: Janos Technology Inc.

Fused Silica (SiO₂ infrared grade)**Fused Silica (SiO₂ ultraviolet grade)****Fused Silica Refractive Index vs. Wavelength**

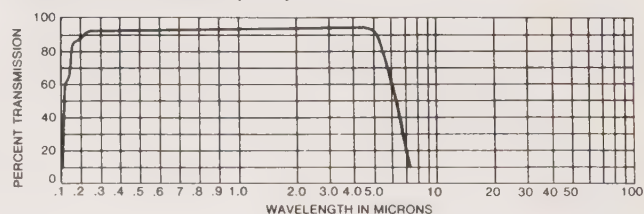
$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
0.22	1.53	0.33	1.48	2.44	1.43
0.23	1.52	0.40	1.47	3.00	1.42
0.24	1.51	0.55	1.46	3.35	1.41
0.26	1.50	1.05	1.45	3.70	1.40
0.29	1.49	1.81	1.44		

Gallium Arsenide (GaAs)**Gallium Arsenide Refractive Index vs. Wavelength**

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
8.0	3.34	13.7	2.90	19.0	2.41
10.0	3.14	14.5	2.82	21.9	2.12
11.0	3.05	15.0	2.73		
13.0	2.97	17.0	2.59		

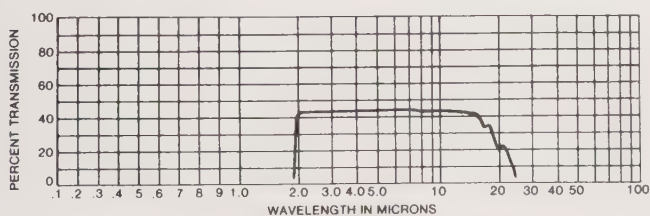
Irtran 2 (ZnS)**Irtran 2 Refractive Index vs. Wavelength**

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
1.00	2.29	5.75	2.24	10.5	2.19
1.24	2.28	7.00	2.23	11.3	2.18
1.50	2.27	8.20	2.22	12.0	2.17
2.25	2.26	9.00	2.21	12.5	2.16
4.00	2.25	9.80	2.20	13.0	2.15

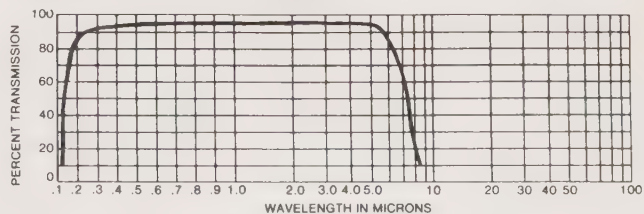
Lithium Fluoride (LiF)**Lithium Fluoride Refractive Index vs. Wavelength**

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
0.20	1.44	0.29	1.41	1.75	1.38
0.22	1.43	0.39	1.40	2.75	1.37
0.24	1.42	0.60	1.39	3.40	1.36

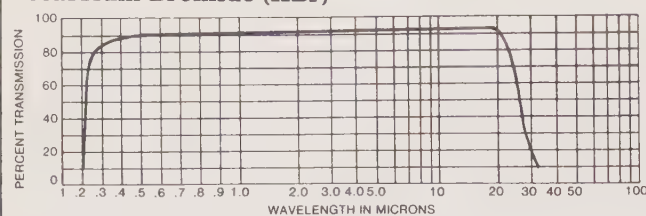
Irtran is a trademark of Eastman Kodak.

Germanium (Ge)**Germanium Refractive Index vs. Wavelength**

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
2.06	4.10	3.00	4.05	8.66	4.00
2.15	4.09	3.42	4.03	9.72	4.00
2.44	4.07	4.26	4.02	11.04	4.00
2.58	4.06	6.24	4.01	13.02	4.00

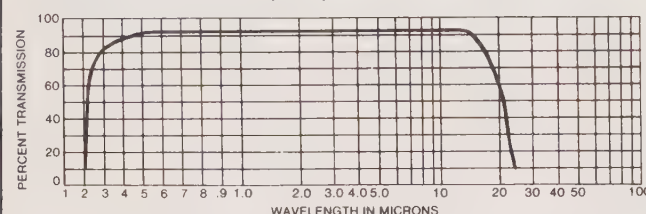
Magnesium Fluoride (MgF₂)**Magnesium Fluoride Refractive Index vs. Wavelength**

$\lambda\mu\text{m}$	n_e	n_o	$\lambda\mu\text{m}$	n_e	n_o
0.20	1.43	1.42	0.34	1.40	1.39
0.23	1.42	1.41	0.56	1.39	1.38
0.27	1.41	1.40			

Potassium Bromide (KBr)

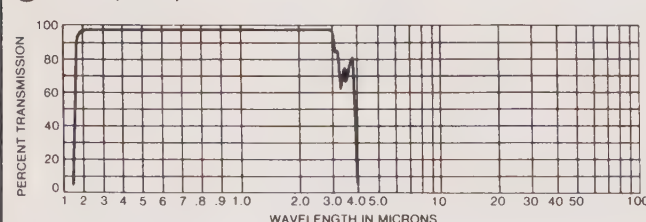
Potassium Bromide Refractive Index vs. Wavelength

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
0.39	1.59	1.50	1.54	20.5	1.49
0.44	1.58	8.50	1.53	22.0	1.48
0.49	1.57	12.0	1.52	23.9	1.47
0.59	1.56	17.0	1.51	25.2	1.46
0.80	1.55	18.1	1.50		

Potassium Chloride (KCl)

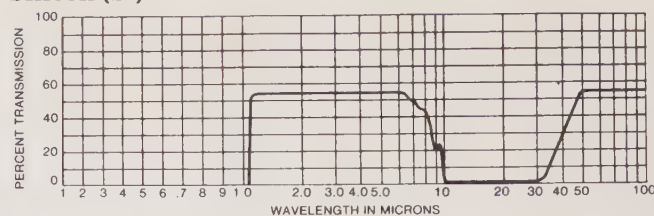
Potassium Chloride Refractive Index vs. Wavelength

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
0.40	1.51	11.7	1.45	20.2	1.39
0.47	1.50	13.5	1.44	21.0	1.38
0.59	1.49	15.0	1.43	22.8	1.37
0.98	1.48	16.7	1.42	23.4	1.36
5.30	1.47	18.1	1.41	24.3	1.35
8.90	1.46	19.1	1.40		

Quartz (SiO₂)

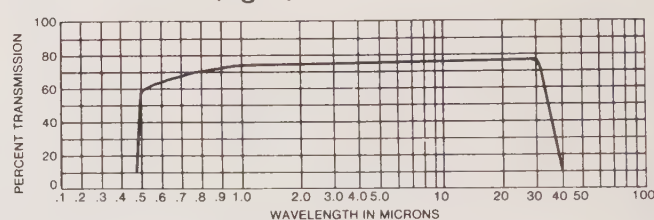
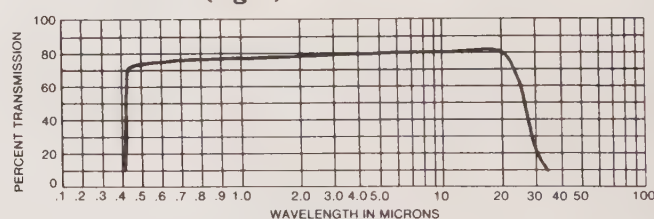
Quartz Refractive Index vs. Wavelength

$\lambda\mu\text{m}$	n_e	n_o	$\lambda\mu\text{m}$	n_e	n_o
0.20	1.66	1.65	0.31	1.59	1.58
0.21	1.65	1.64	0.33	1.58	1.57
0.22	1.64	1.63	0.38	1.57	1.56
0.23	1.63	1.62	0.49	1.56	1.55
0.24	1.62	1.61	0.77	1.55	1.54
0.25	1.61	1.60	1.30	1.54	1.53
0.27	1.60	1.59	2.05	1.53	1.52

Silicon (Si)

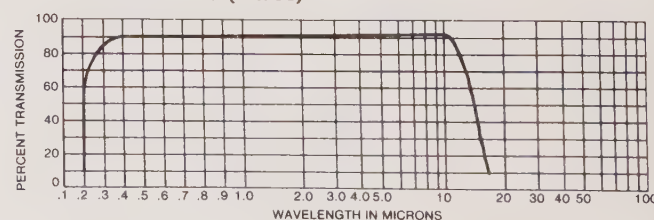
Silicon Refractive Index vs. Wavelength

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
1.40	3.49	1.82	3.46	3.30	3.43
1.50	3.48	2.05	3.45	6.00	3.42
1.66	3.47	2.50	3.44		

Silver Bromide (AgBr)n = 2.3 at 0.45 μm **Silver Chloride (AgCl)**

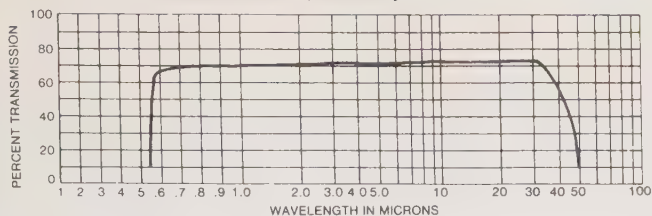
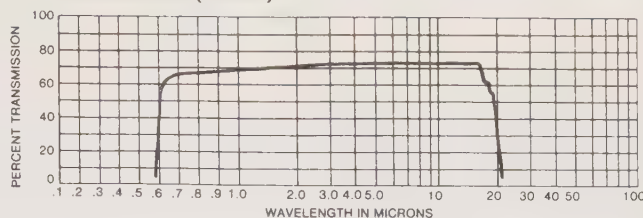
Silver Chloride Refractive Index vs. Wavelength

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
0.50	2.10	1.55	2.01	13.7	1.96
0.60	2.06	3.90	2.00	15.2	1.95
0.70	2.05	7.50	1.99	16.2	1.94
0.85	2.03	10.0	1.98	17.6	1.93
1.00	2.02	12.0	1.97	18.7	1.92

Sodium Chloride (NaCl)

Sodium Chloride Refractive Index vs. Wavelength

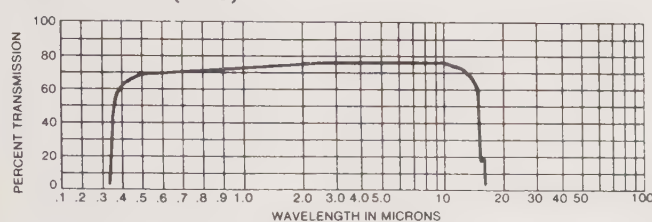
$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
0.35	1.58	1.25	1.53	12.0	1.48
0.37	1.57	4.50	1.52	13.1	1.47
0.46	1.56	7.30	1.51	14.2	1.46
0.51	1.55	9.50	1.50	15.1	1.45
0.68	1.54	10.6	1.49	16.0	1.44

Thallium Bromiodide (KRS-5)**Zinc Selenide (ZnSe)****Thallium Bromiodide Refractive Index vs. Wavelength**

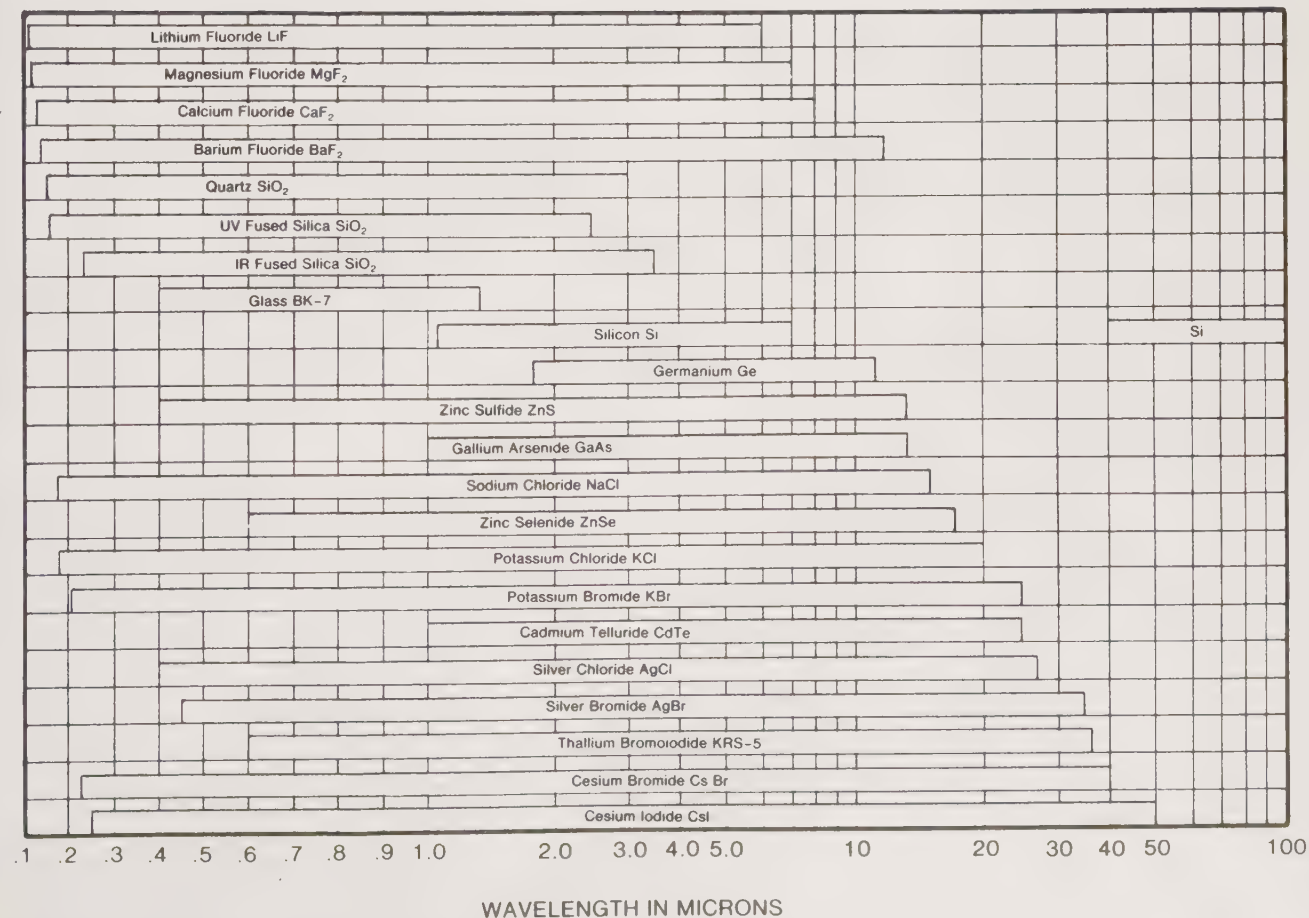
$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
1.45	2.41	10.3	2.37	22.4	2.33
1.75	2.40	14.3	2.36	24.5	2.32
2.30	2.39	17.5	2.35	26.4	2.31
4.80	2.38	20.1	2.34	28.0	2.30

Zinc Sulfide Refractive Index vs. Wavelength

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
1.00	2.29	5.75	2.24	10.5	2.19
1.24	2.28	7.00	2.23	11.3	2.18
1.50	2.27	8.20	2.22	12.0	2.17
2.25	2.26	9.00	2.21	12.5	2.16
4.00	2.25	9.80	2.20	13.0	2.15

Zinc Sulfide (ZnS)**Zinc Selenide Refractive Index vs. Wavelength**

$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n	$\lambda\mu\text{m}$	n
2.75	2.44	12.5	2.39	17.8	2.34
5.00	2.43	13.5	2.38	18.5	2.33
7.50	2.42	15.0	2.37	19.3	2.32
9.50	2.41	16.0	2.36	20.0	2.31
11.0	2.40	16.9	2.35		

TRANSMISSION RANGES FOR SOME MATERIALS

Refractive Indices of Fused Silica

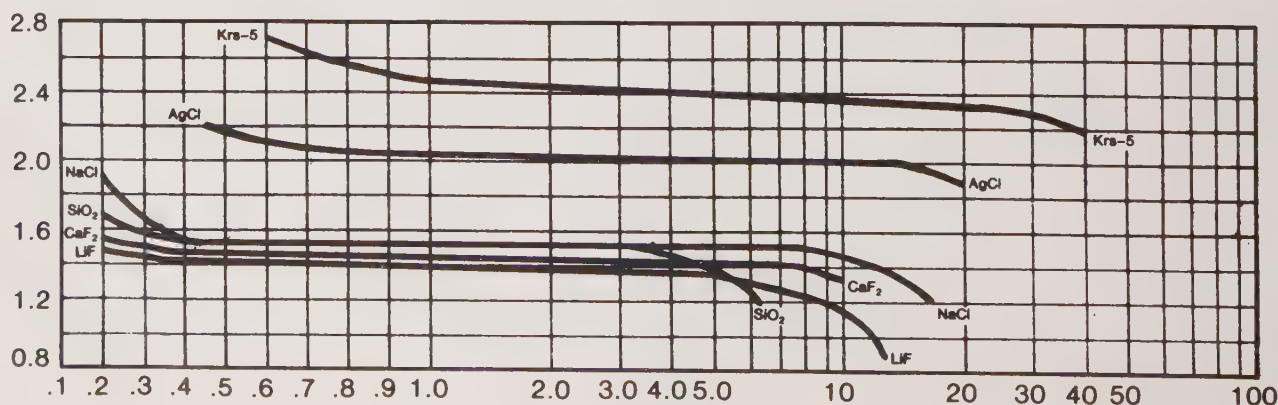
Wavelength (micrometers)	Spectral Source	Index	Wavelength (micrometers)	Spectral Source	Index
0.213856	Zn	1.534265	0.643847	Cd	1.456708
0.214438	Cd	1.533701	0.656272	H	1.456372
0.226747	Cd	1.522818	0.667815	He	1.456073
0.230209	Cd	1.520050	0.706519	He	1.455157
0.237833	Hg	1.514752	0.852111	Cs	1.452468
0.239938	Hg	1.513369	0.894350	Cs	1.451840
0.248272	Hg	1.508397	1.01398	Hg	1.450245
0.265204	Hg	1.500004	1.08297	He	1.449406
0.269885	Hg	1.498043	1.12866	Hg	1.448877
0.275278	Hg	1.495921	1.3622	Hg	1.446198
0.280347	Hg	1.494030	1.39506	Hg	1.445840
0.289360	Hg	1.491012	1.4695	Cs	1.444984
0.296728	Hg	1.488722	1.52952	Hg	1.444274
0.302150	Hg	1.487192	1.6606	TCB ^a	1.442651
0.330259	Zn	1.480549	1.681	Poly ^b	1.442404
0.334148	Hg	1.479762	1.6932	Hg	1.442254
0.340365	Cd	1.478586	1.70913	Hg	1.442060
0.346620	Cd	1.477456	1.81307	Hg	1.440692
0.361051	Cd	1.475120	1.97009	Hg	1.438531
0.365015	Hg	1.474524	2.0581	He	1.437215
0.404656	Hg	1.469617	2.1526	TCB	1.435744
0.435835	Hg	1.466694	2.32542	Hg	1.432925
0.467816	Cd	1.464295	2.4374	TCB	1.430933
0.486133	H	1.463131	3.2439	Poly	1.413147
0.508582	Cd	1.461864	3.2668	Poly	1.412535
0.546074	Hg	1.460079	3.3026	Poly	1.411565
0.576959	Hg	1.458849	3.422	Poly	1.408222
0.579065	Hg	1.458775	3.5070	Poly	1.405656
0.587561	He	1.458462	3.5564	TCB	1.404145
0.589262	Na	1.458407	3.7067	TCB	1.399375

^aTCB = 1,2,4 - Trichlorobenzene^bPoly = Polystyrene

Wavelength (micrometers)	Laser Source	Index	Wavelength (micrometers)	Laser Source	Index
0.4880	A	1.463015	0.840	GaAs	1.452655
0.5682	Kr	1.459177	1.060	CO ₂	1.449679
0.6328	HeNe	1.457018	1.060	Nd in glass	1.449679
0.6943	Ruby	1.455424	1.0648	Nd-YAG	1.449621

SOURCE: DYNASIL CORPORATION

Plot of Refractive Index vs. Wavelength for Some Materials



Optical Components

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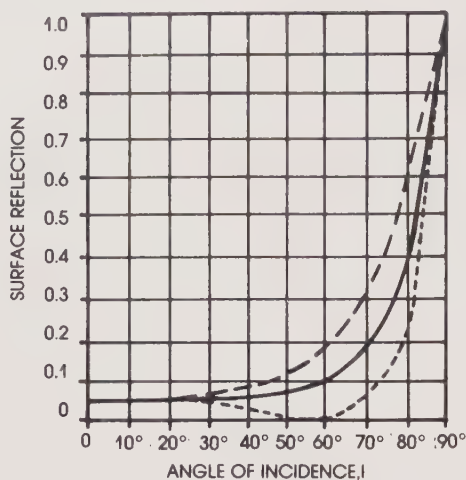
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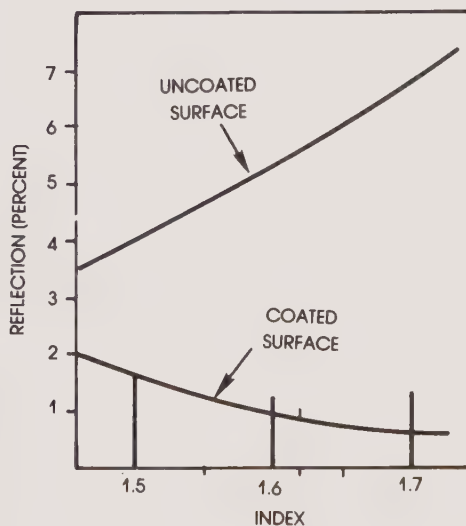
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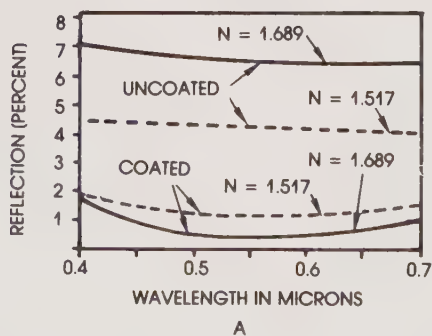
Reflection at an Air-To-Glass Interface



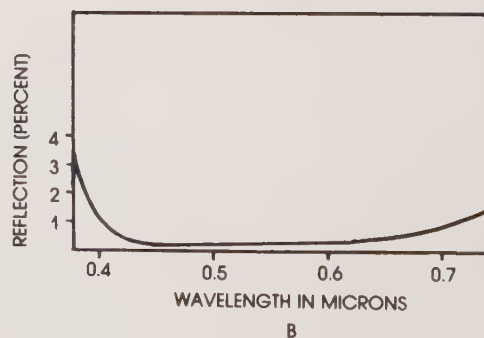
Reflection from a single air-glass interface for index 1.523 (C-1 glass). Solid line: reflection of unpolarized light. Dashed line: reflection of light polarized so that the electric vector is perpendicular to the plane of incidence. Dotted line: reflection of light polarized so that the electric vector is parallel to the plane of incidence.



The measured reflection of white light from an uncoated surface and from a surface coated with a quarter-wave MgF_2 low-reflection coating, as a function of the index of the base material.



(A) The measured spectral reflectivity of a single-layer low-reflection coated glass surface compared with the reflectivity of uncoated glass. Coating is a quarter-wave MgF_2 film on BSC-2 (517:645) (dashed curves) and on EDF-2 (689:309) (solid curves).



(B) A high-efficiency multilayer low-reflection coating on BSC-2 glass. Note the improvement over the single-layer coating.

SOURCE: Smith, Warren J. (1966). *Modern Optical Engineering*.

Characteristics of Acousto-Optic Scanning Devices

MODULATORS					
Material	Bandwidth	Rise Time	Acoustic Input Power (Saturation)	Material Optical Wavelength Range	Efficiency at Maximum Bandwidth (633 nm)
Glass	5–10MHz	50ns	1–6.0 watts	.4–25 μ	>70%
PbMoO ₄	>80MHz	4–6ns	.5 – 1.5 watts	.42 – 5.5 μ	>70%
TeO ₂	>80MHz	4–6ns	.5 – 1.5 watts	.35 – 5 μ	>70%
Germanium	10MHz	70ns	20 – 30 watts	2 – 20 μ	>50%

DEFLECTORS				
Type	Resolution	Scan Speed	Acoustic Power	Optical Wavelength Range
PbMoO ₄	>1500	15 spots/ μ s	<5 watts	.42 – 5.5 μ
TeO ₂	>2000	10 spots/ μ s	<5 watts	.35 – 5 μ
Glass	<1000	10 spots/ μ s	<5 watts	.4 – 2.5 μ
Germanium	600-800	5 spots/ μ s	100-150 watts	2 – 20 μ
TeO ₂ Chirp	~2000	>20 spots/ μ s	<1 watt (average)	.35 – 5 μ

Typical Acousto-Optic Figures of Merit

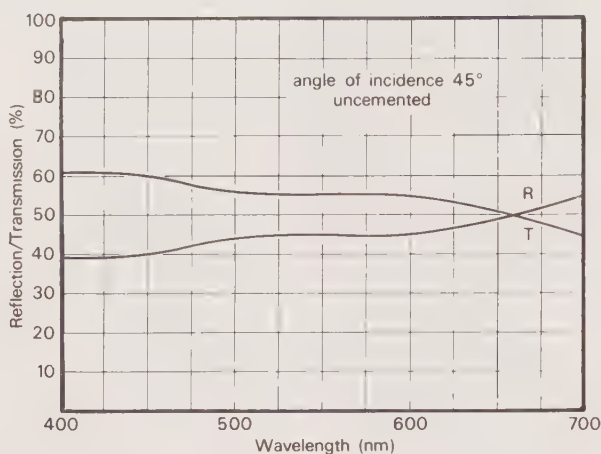
Material	Acoustic Mode	Figure of Merit (M ₂)	Acoustic Velocity
Flint Glass (SF-4)	Longitudinal	$4.51 \times 10^{-15} \text{sec}^3/\text{kg}$	3.63mm/ μ sec
TeO ₂	Longitudinal	$34.5 \times 10^{-15} \text{sec}^3/\text{kg}$	4.2mm/ μ sec
TeO ₂	Shear	$793 \times 10^{-15} \text{sec}^3/\text{kg}$	.617mm/ μ sec
PbMoO ₄	Longitudinal	$36.3 \times 10^{-15} \text{sec}^3/\text{kg}$	3.63mm/ μ sec

SOURCE: ISOMET INC.

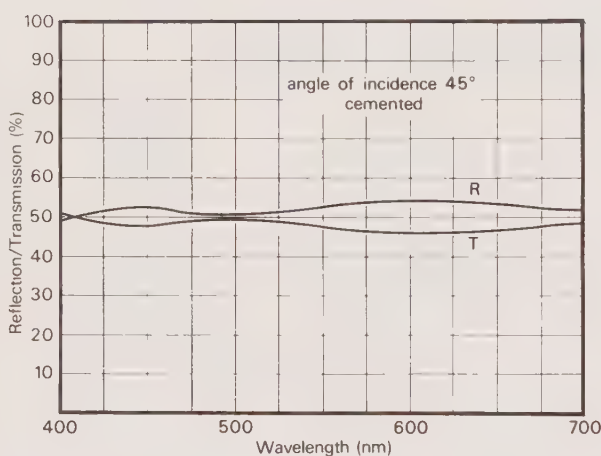
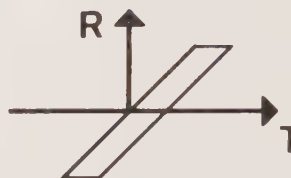
Problems and Solutions for Acousto-Optic Processor Devices

Cause	Problem	Solution
Transducer impedance mismatch	Limited bandwidth	Acoustic impedance matching (quarter-wave layers)
	Quadratic phase error	Quarter-wave matching, frequency plane phase filter
Acousto-optic interaction	Limited bandwidth	Birefringent diffraction Beam steering
Acoustic dispersion	Frequency distortion/frequency blurring	Increasing interaction length (limited bandwidth)
		Optical beam apodization
		Increasing transducer height
		Acoustic beam apodization
		Birefringent diffraction Material selection
Optical diffraction	Limited resolution	Increasing aperture
	Side lobes	Optical beam apodization
Acoustic diffraction	Fresnel pattern distortion	Frequency plane filtering
		Acoustic beam apodization Material selection

Neutral Beamsplitters

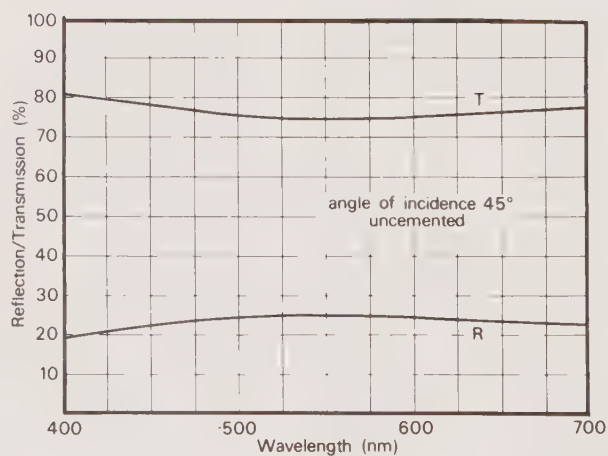
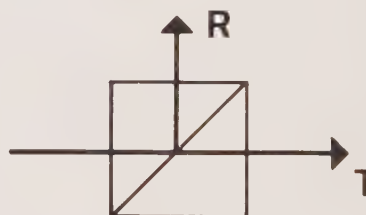


R:T = 45:55 for 550 nm/Flat Plate/ 45°



R:T = 50:50/Cube/ 45°

Standard Specification:
R:T = $50:50 \pm 5\%$ at 550 nm
(R:T = $50:50 \pm 8\%$ at 440-650 nm)

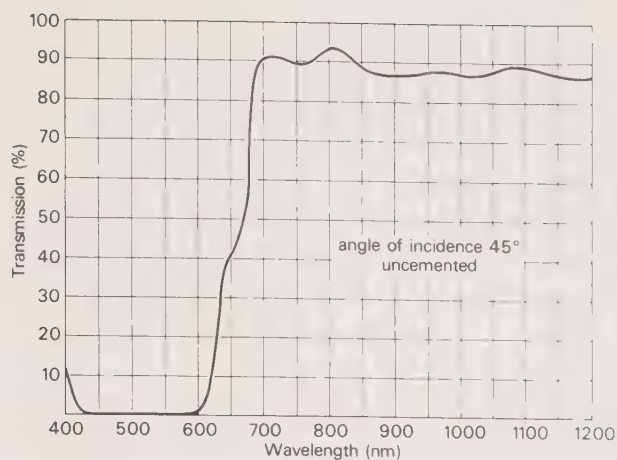


R:T = 25:75/Flat Plate/ 45°



SOURCE: BALZERS CORP.

Dichroic Beamsplitters

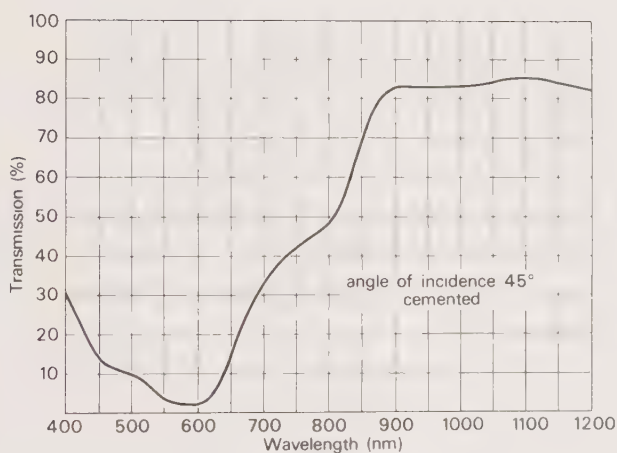
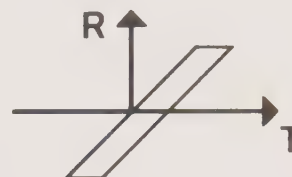


R Visible/T 1.06 μ /Flat Plate/45°

Standard Specification:

R $\geq 92\%$ visible

T $\geq 85\%$ at 1.06 μ



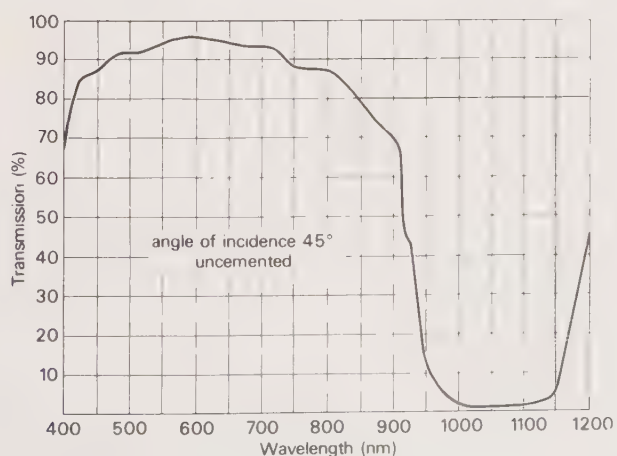
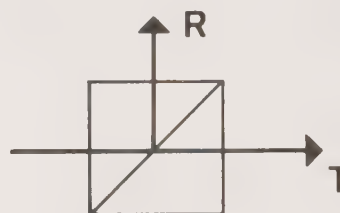
R Visible/T 1.06 μ /Cube/45°

Standard Specification:

R $\geq 90\%$ at 550 nm

R $\geq 80\%$ at 440-650 nm

T $\geq 80\%$ at 1.06 μ

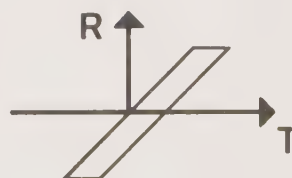


T Visible/R 1.06 μ /Flat Plate/45°

Standard Specification:

T visible $\geq 94\%$

R 1.06 μ $\geq 98\%$

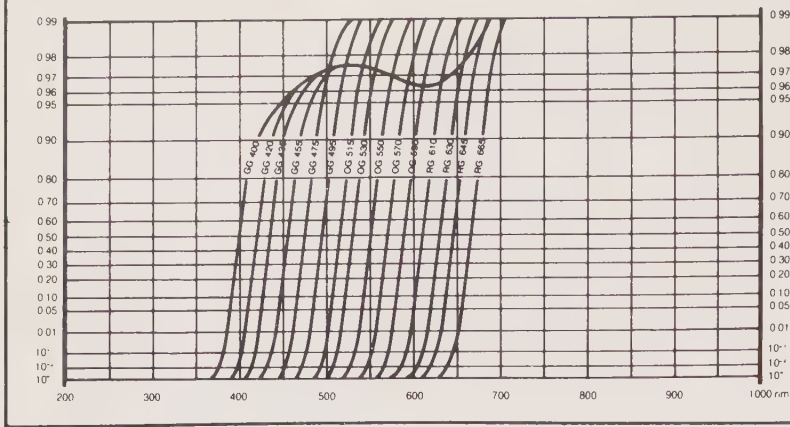


To choose the product most suitable to your requirements, you should have detailed information on: wavelength range; reflection and transmission values; angle of incidence; configuration (flat plate or cube); energy level; substrate material; and plane of polarization.

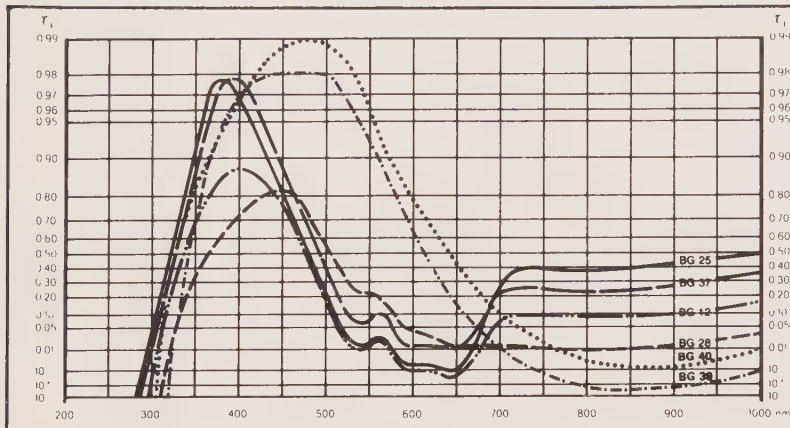
SOURCE: BALZERS CORP.

Filter Glass Transmission

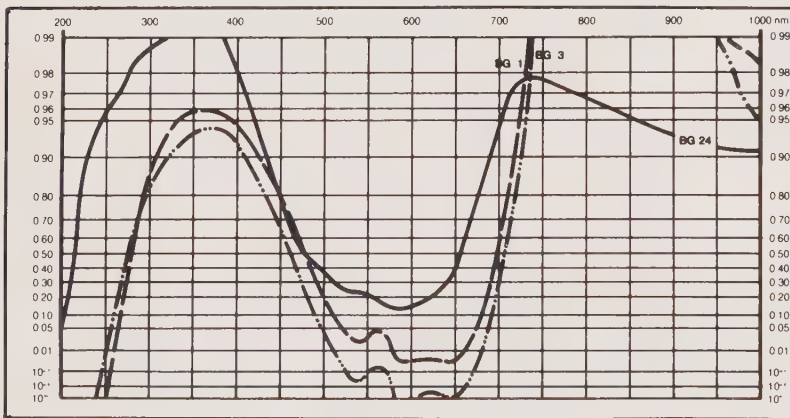
SOME OF THE SCHOTT SHORT WAVE CUT-OFF FILTERS. THICKNESS: 3MM.



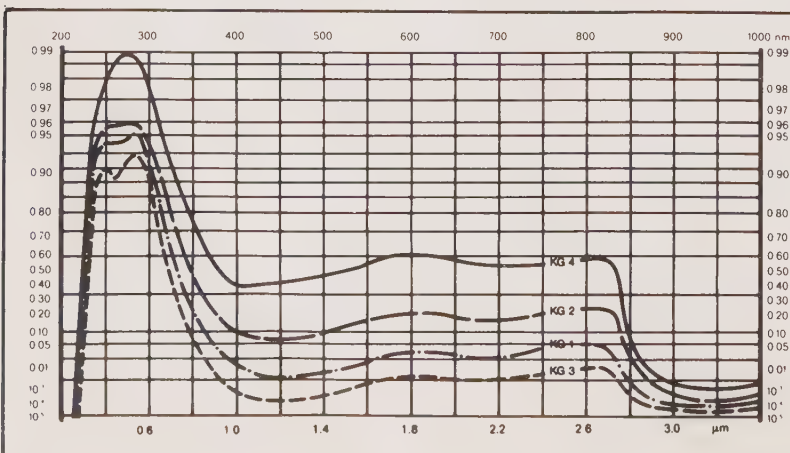
SOME OF THE SCHOTT BANDPASS-TYPE FILTERS. TRANSMITTING BLUE, ABSORBING ULTRAVIOLET, RED AND INFRARED. THICKNESS: 1MM.

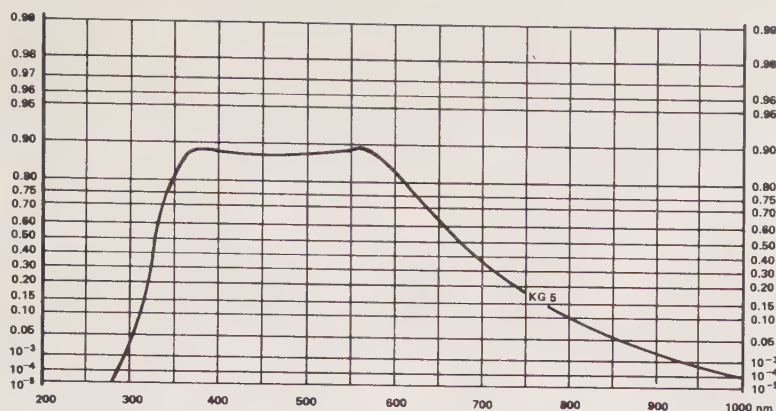


SOME SCHOTT REJECTION FILTERS. REJECTS (ABSORBS) GREEN TO RED VISIBLE LIGHT BUT TRANSMITS NEAR-ULTRAVIOLET, BLUE AND NEAR-INFRARED. THICKNESS: 1MM.



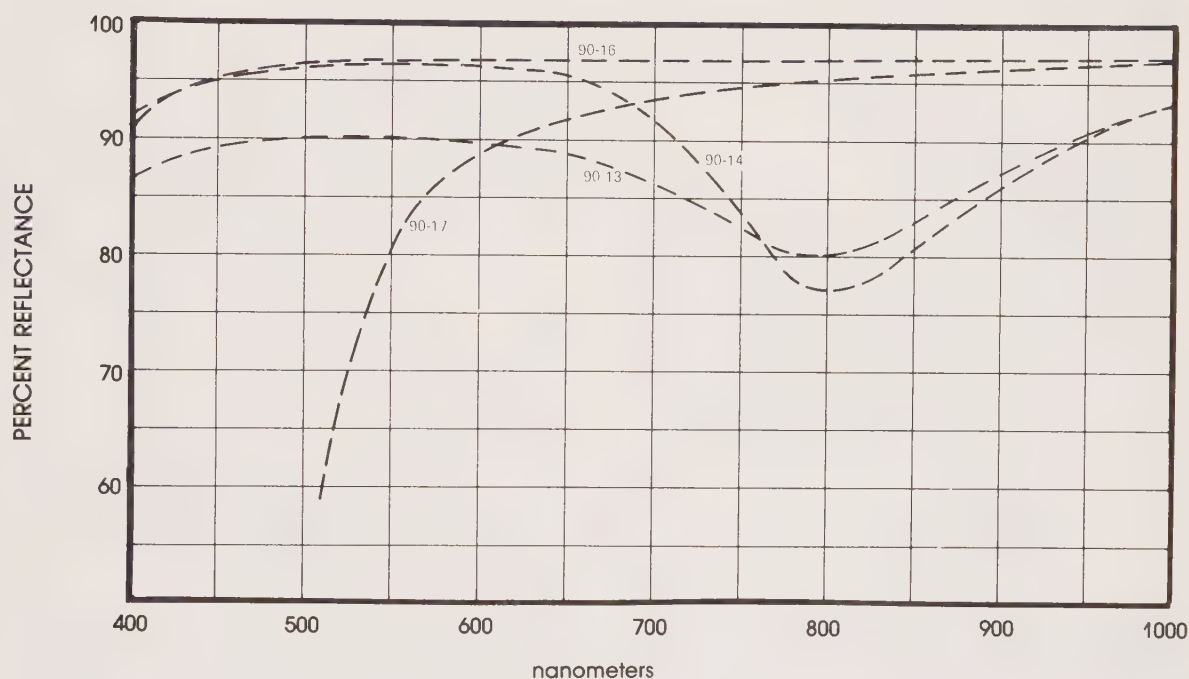
SOME SCHOTT FILTERS SUITABLE FOR PASSING VISIBLE BUT REJECTING INFRARED. THICKNESS: 2MM.





SCHOTT KG5 HEAT ABSORBING GLASS
TRANSMITTANCE CURVE.
THICKNESS: 2MM.

First Surface Mirrors — Normal to 45° Incidence



90-13 Protected Aluminum: The 90-13 coating is a thin opaque layer of aluminum overcoated with a transparent dielectric protective layer to provide maximum durability. The average white light reflectance will be 86 percent minimum. This coating is fully capable of meeting the performance and durability requirements of MIL-M-13508B.

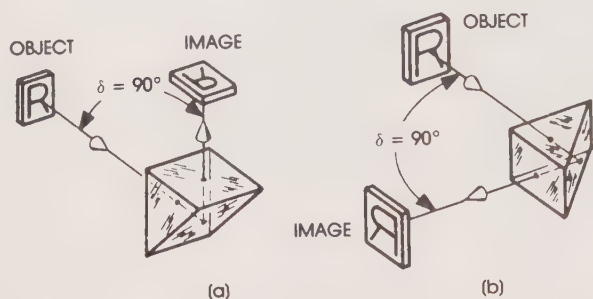
90-14 Enhanced Aluminum: The 90-14 coating gives a higher reflectance than the 90-13 coating. It consists of a thin opaque layer of aluminum overcoated with several transparent dielectric layers to provide a reflectance higher than that of protected aluminum. Coating 90-14 has an average reflectance of 94 percent over the visible spectrum. This coating will withstand normal environmental conditions and will meet the durability requirements of MIL-M-13508B.

90-16 Durable Silver: The 90-16 coating is a specially deposited durable first surface coating of silver. The average reflectance from 0.450 to 0.8 micrometer is 96 percent or higher. This coating is fully capable of meeting the performance requirements of MIL-M-13508B.

90-17 First Surface Gold: The 90-17 coating is a special alloy gold coating for high reflectance in the infrared. The average reflectance from 0.8 micrometer through the far infrared exceeds 96 percent. This coating can be applied to metal or glass and is environmentally stable to 700°F or higher. This coating passes the tape test and will withstand careful optical cleaning.

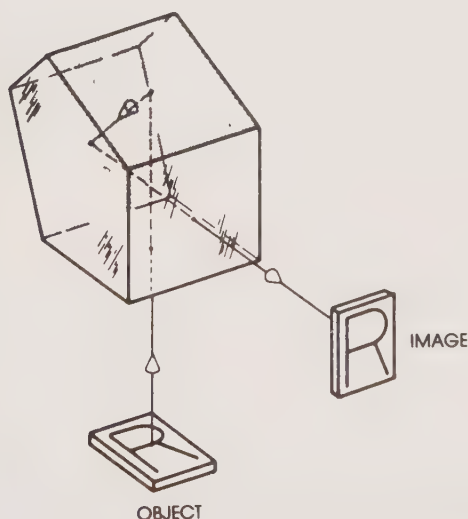
SOURCE: BAUSCH AND LOMB INC.

Prisms Frequently Used in Optical Systems



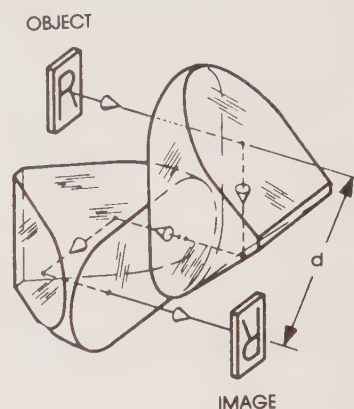
Right-angle prism

This single prism will deviate the line of sight through an angle $\sigma = 90^\circ$. The image will be inverted when the prism is turned through an angle of 90° , as shown in (b).



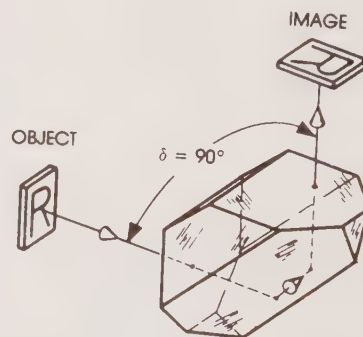
Penta prism

This prism will neither revert nor invert the image, but will simply deviate the line of sight through a 90° angle.



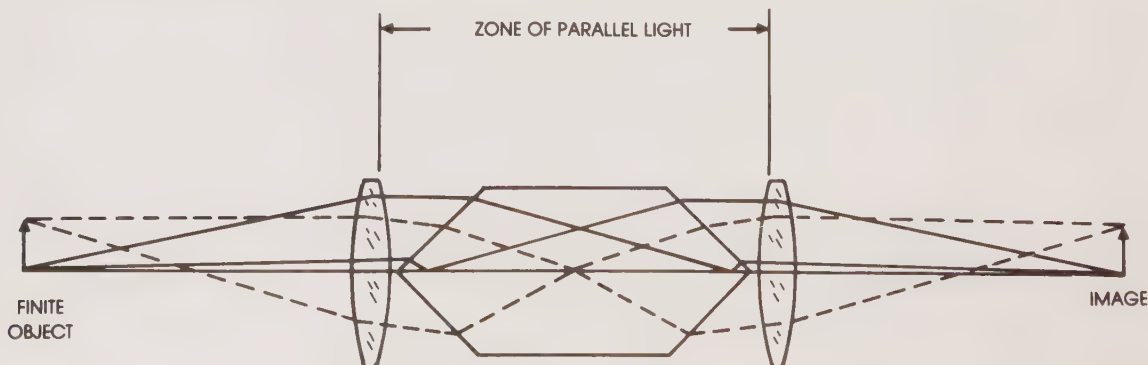
Porro prism system

In 1850, an Italian engineer named Porro designed the prism system here. This prism is made up of two right-angle prisms, usually identical in construction, placed at right angles to each other. It is a direct-vision prism system, but the axis is displaced by the amount d . The system will invert and revert the image.



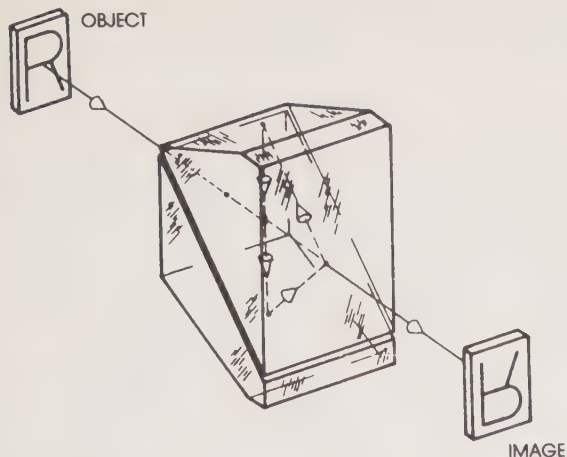
Amici prism

The Amici prisms will revert and invert the image, and at the same time, will deviate the line of sight through an angle σ to 90° .



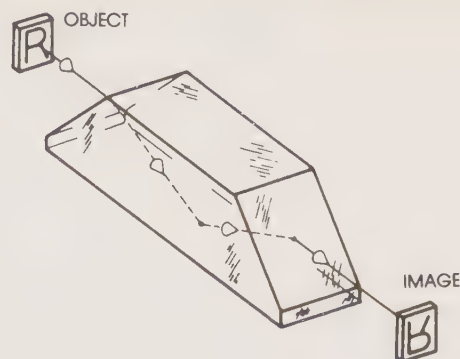
Double Dove prism

This twin prism consists of two Dove prisms. Their reflecting surfaces are silvered and then the two halves are cemented together. This method cuts the length of the single Harting-Dove prism in half. It performs like a single Harting-Dove prism, and it must only be placed in parallel light.



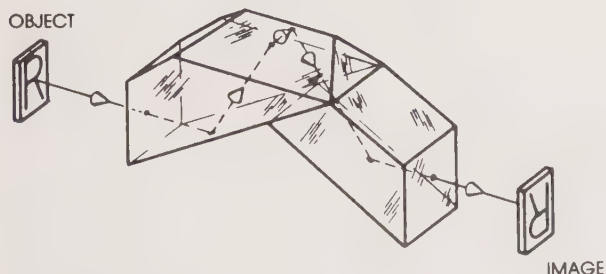
Pechan prism

The Pechan prism performs much like the Dove prism, but it may be placed in convergent or divergent light, permitting a reduction of instrument size. It will invert (shown here) or revert the image, depending on its orientation. It may also displace the line of sight if not properly centered, but will not deviate it.



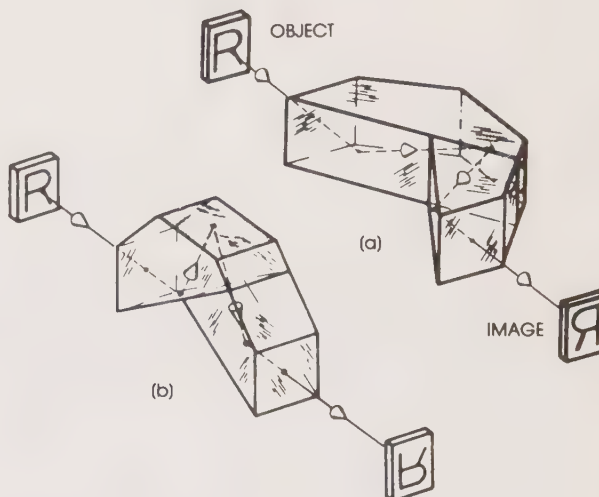
Dove prism

This direct-vision prism is made in one piece. The image will be inverted when the prism is held as shown in the figure, and is inverted when the prism is turned about the axis through an angle of 90° . It can only be used in parallel light.



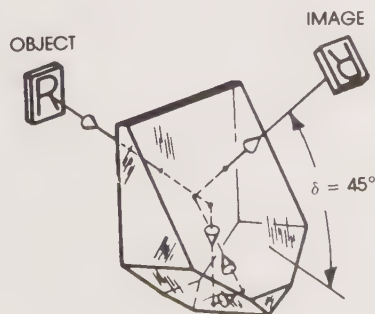
Abbé prism, type A

This prism inverts and reverts the image, but will not deviate the line of sight. As a result, it's a direct-vision prism. It is made in two pieces cemented together.



Reversion prism

This prism, a modification of the Abbé prism type A, is made up of two elements which are cemented together. Like the Pechan prism, it may be placed in the path of parallel, converging, or diverging beams of light. Because three reflections are involved, it may be used to revert (a) or invert (b) the image, depending on its orientation.



Schmidt prism

The Schmidt prism will revert and invert the image, and at the same time, it will deviate the line of sight through an angle $\sigma = 45^\circ$.

Bruce Walker
Kollmorgen Corp.

The above material was extracted from the Military Handbook-141, released in 1962 by the Dept. of Defense, and an excellent reference on optical theory and design.

Mirrors: Applications

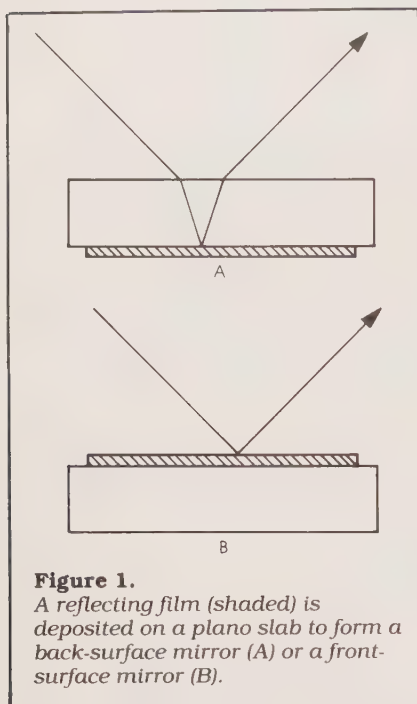


Figure 1.

A reflecting film (shaded) is deposited on a plano slab to form a back-surface mirror (A) or a front-surface mirror (B).

Mirrors serve manifold functions, some of which are the following. They are used as components of imaging systems: Many astronomical photographic objectives, such as the Palomar reflector, use parabolic or spherical mirrors, and numerous microscopes and telephoto SLR camera lenses contain catadioptric optics with one or more reflecting surfaces. Plano mirrors are widely used to fold the optical path and thus make an imaging system more compact, and also to erect or invert images in such systems.

Mirrors are employed too in non-imaging systems to direct the luminous flux into the image plane, as in the illuminator of a projector, and reflect the sun's flux — thermal control mirrors are important components for the control of the temperature of space vehicles. Those that are partially transmitting are used at non-normal incidence as beamsplitters. Finally, mirrors also direct the flux from an optical amplifier back onto itself, thus creating a laser.

Front-and back-surface mirrors

In the case where a plano sheet of transparent material, such as a glass slab, functions as a mirror, it can be classed as either front-surface or back-surface.

As shown in Figure 1, the flux impinging upon a back-surface mirror

traverses the slab, reflects from the rear mirrored surface and exits from the slab. Such mirrors are commonly used for several reasons: The coating on the rear surface is well protected and thus does not degrade when exposed to high humidity, salt, fog,

sand abrasion and so on. For example, the mirrors that direct the sun at the "power tower" near Barstow, California, are back-surface. Another attribute of a rear-surface mirror is a relatively high emissivity in the infrared; thus thermal control mirrors

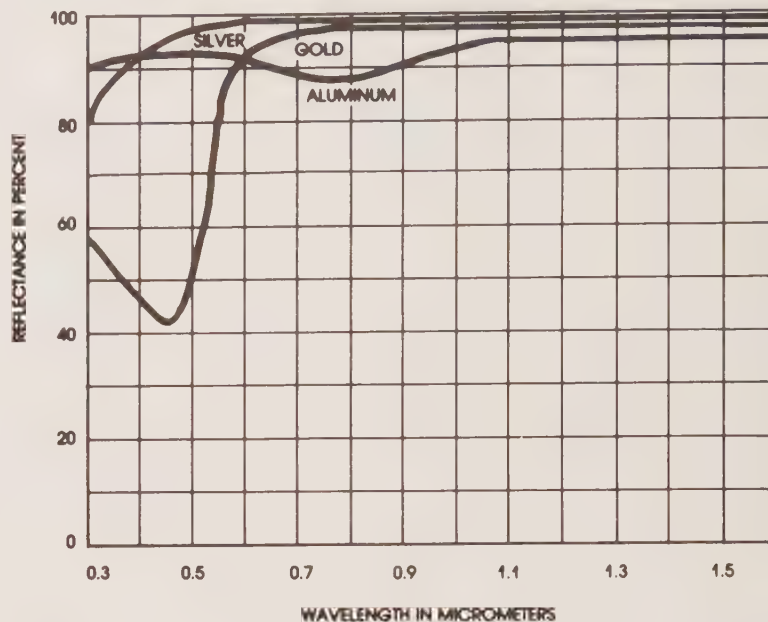


Figure 2.

Radiant reflectance of single opaque evaporated metallic layers.

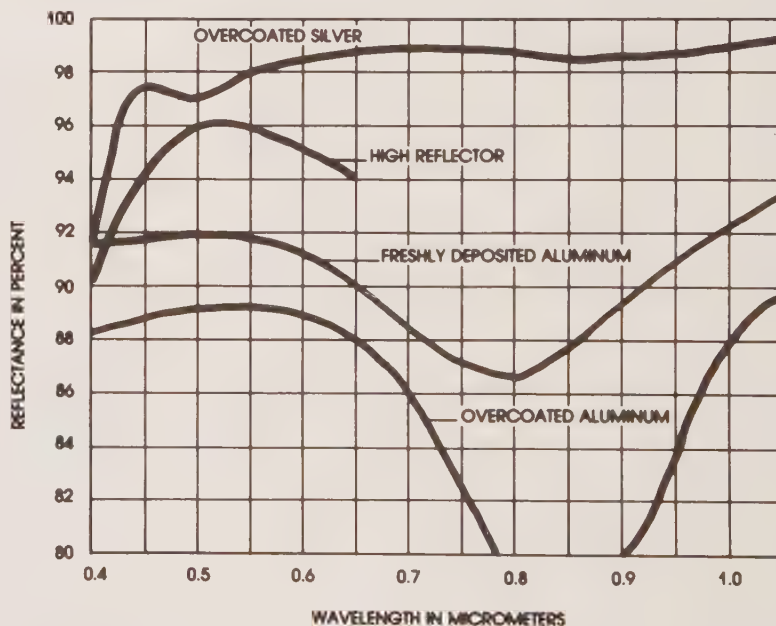


Figure 3.

Reflectance vs. wavelength of an evaporated aluminum film, as well as several coatings containing one or more nonmetallic layers, for front-surface reflectors.

on space vehicles are back-surface mirrors, because they serve to reflect most of the sun's radiation, yet radiate effectively so that the temperature is relatively low. The disadvantage of the back-surface mirror is that if the optical system is imaging, then the slab of glass must be optically homogeneous — and hence more expensive than a front-surface mirror.

As stated above, the advantage of the front-surface mirror is that if the surface is totally reflecting, then the glass (ULE™, Cer-Vit™, Zero-Dur™, etc.) need not be of optical quality.

A commonly used front-surface mirror coating is aluminum overcoated with silicon monoxide. A layer about one-half wave thick in the visible region (physical thickness = 150nm) slightly increases reflectance and protects the surface against corrosion and abrasion. While the aluminum is relatively soft, the overcoat usually allows the surface to be gently cleaned to remove dust or air-carried contaminants. Typically, the SiO is slightly absorbing at wavelengths shorter than 500nm, but the long-term performance justifies such an overcoat on the bare aluminum. A reflectance in the range of 89 to 90 percent is typical.

In the ultraviolet region, aluminum is an excellent reflector of wavelengths as short as 150nm. A film of magnesium fluoride, commonly used as an overcoat in the UV, not only protects the surface, but enhances the reflectance at wavelengths near 120nm.

Coatings employing silver are frequently used to obtain a high reflectance across a broad spectrum. An overcoat of one or more dielectric layers is mandatory, since unprotected silver tarnishes rapidly. Reflectance of 96 to 98 percent can be obtained in this manner. A disadvantage of silver is that its reflectance is subject to greater environmental degradation than are aluminum and gold reflectors. Although improved multilayer overcoating techniques have, in recent years, increased the hardness of silver mirrors, they are still more expensive than aluminum mirrors.

Figure 2 depicts the reflectance of metallic mirrors of silver, aluminum and gold; Figure 3 shows the reflectance of some overcoated mirrors.

Reflectors for the infrared

A thin opaque film such as gold has a quite substantial reflectance at a wavelength of 1 μ m, as shown in Figure 2. Such a film reflects well at wavelengths as long as 50 μ m. Al-

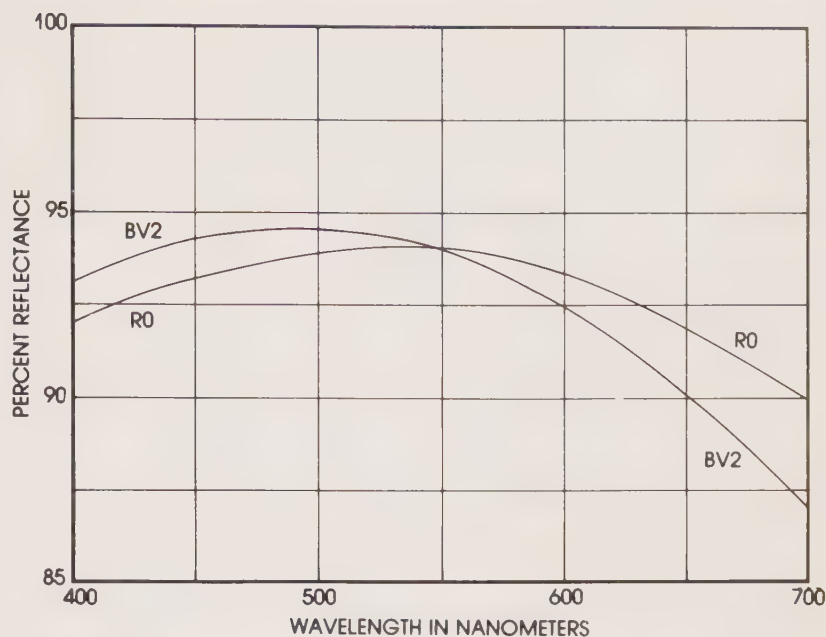


Figure 4.

Reflectance at 45° incidence angle of enhanced aluminum typical first surface mirrors.

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Frames	1-6" Alum. Circles. 5x7" Alum. Rectangles.	You supply frames or we machine to your specs. Brass. Aluminum. Ceramic. Stainless. Others. Oval. Square. Rectangular. Truncated Cylinders.
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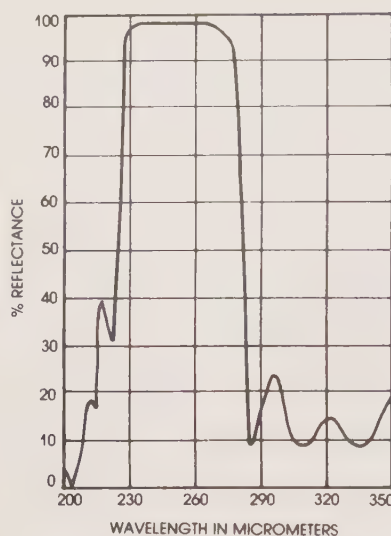
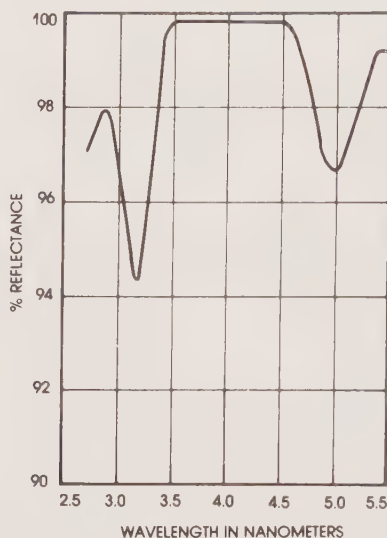


Figure 6.
An overcoated metallic reflector for the IR.

Figure 5.
The measured reflectance of a multilayer dielectric reflector for the UV.



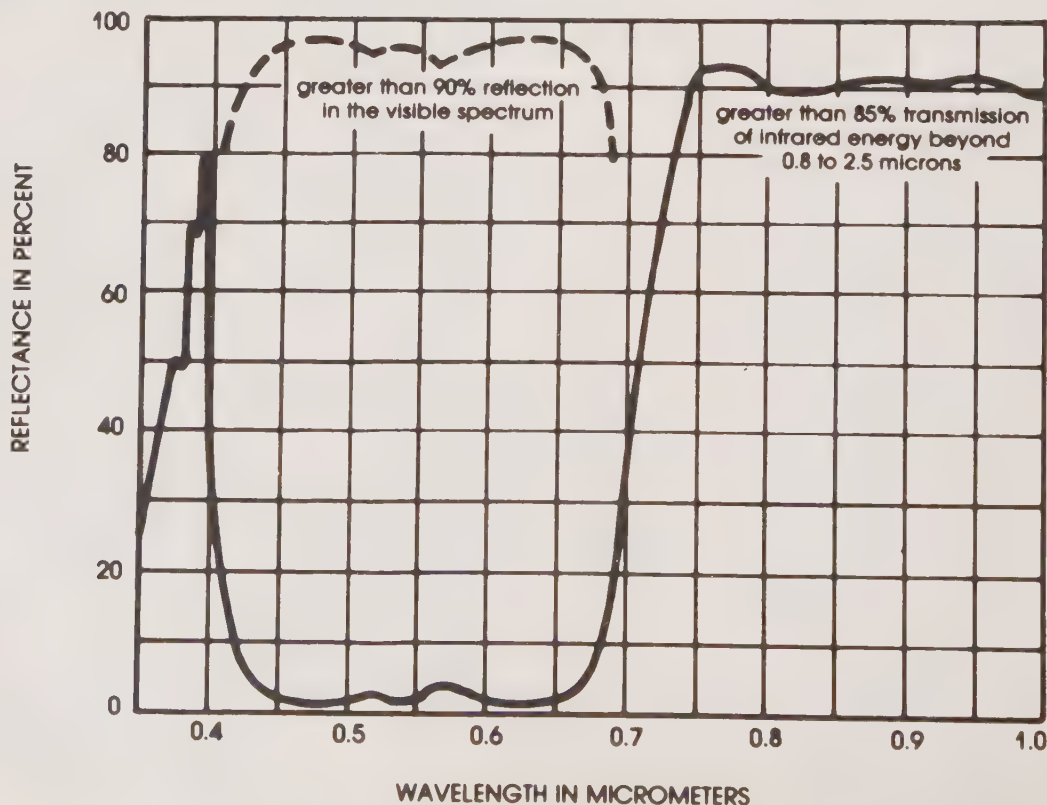
though silver has a slightly higher reflectance than gold, it cannot withstand harsh environmental conditions. However, gold is so soft that it cannot be touched to remove accumulated dirt, and thus it is not usually used except in a laboratory. Electroplated gold, more durable than that which is vacuum-deposited, has the advantage that it may be deposited on convoluted surfaces. Evaporated gold may also be overcoated to enhance both its reflectance and durability.

Mirrors are sometimes made from other sputtered, evaporated, plated or polished bulk metals for infrared applications. Copper offers high reflectance with good thermal properties — although it may tarnish — and molybdenum offers high resistance to damage by long-wavelength lasers. Rhodium surfaces have the advantage that they are immune to salt-water corrosion even after extended immersion.

Mirrors with enhanced reflectance

There are many uses for mirrors with an enhanced reflectance over a narrow spectral region. They are used as folding or scanning mirrors

Figure 7.
Spectral reflectance (dashed) and transmittance (solid) of a "cold mirror."



in photocopiers — a reflectance of 95 percent is typically attained over the 100nm spectral region where the photoconductor (i.e., selenium, cadmium sulfide, zinc oxide, etc.) has a relatively high responsivity. The $R(\lambda)$ of two such mirrors is depicted in Figure 4.

There are many lasers, such as Nd:YAG, HeNe and CO₂, that require a relatively high reflectance over a relatively narrow band of wavelengths. As an example, Figure 5 shows the spectral reflectance of a coating whose R exceeds 99 percent at wavelengths near 250nm in the ultraviolet. As depicted in Figure 6, an even higher reflectance — in excess of 99.9 percent — may be obtained at wavelengths in the infrared, in the vicinity of those of the deuterium fluoride laser.

Mirrors for heat control

The ability to transmit as well as reflect flux is the great advantage of coatings containing as many as forty nonmetallic layers. Radiant flux (heat) and luminous flux (light) are separated in slide and movie projectors, photocopiers and dental illuminators by combinations of "cold mirrors" and "hot mirrors." A cold mirror will typically reflect more than 90 percent of the visible spectrum (comparable to aluminum) while transmitting 85 percent or more of the heat energy out to a wavelength of 2.5 μ m. The $R(\lambda)$ of a cold mirror is shown in Figure 7. This permits brighter pictures without burning the film in a projector. The inverse of the cold mirror reflects heat in the near IR, while transmitting the desired visual wavelengths (see Figure 8). By adjusting the design, the wavelengths to be split can be chosen almost at will.

Variants of the hot and cold mirror designs, called dichroics, are used to separate colors, such as in three-tube color television cameras. Separation efficiency is much greater than when using absorbing glass or gelatin filters. In addition, the wavelength bands may be selected a little more arbitrarily. Dr. Gary S. Ash/
Engineering Staff, OCLI Inc.

Dr. Gary S. Ash, now of Instruments SA, was the original author of this article, and the engineering staff of Optical Coating Laboratory Inc., revised it under the coordination of Dick Vegsund. ULE and Pyrex are registered trademarks of Corning Glass Works. Cer-Vit a registered trademark of Owens Illinois, and Zero-Dur a registered trademark of Schott Optical Glass Inc. All of the figures in this article © 1982 OCLI, Santa Rosa, Calif. Reprinted with permission.

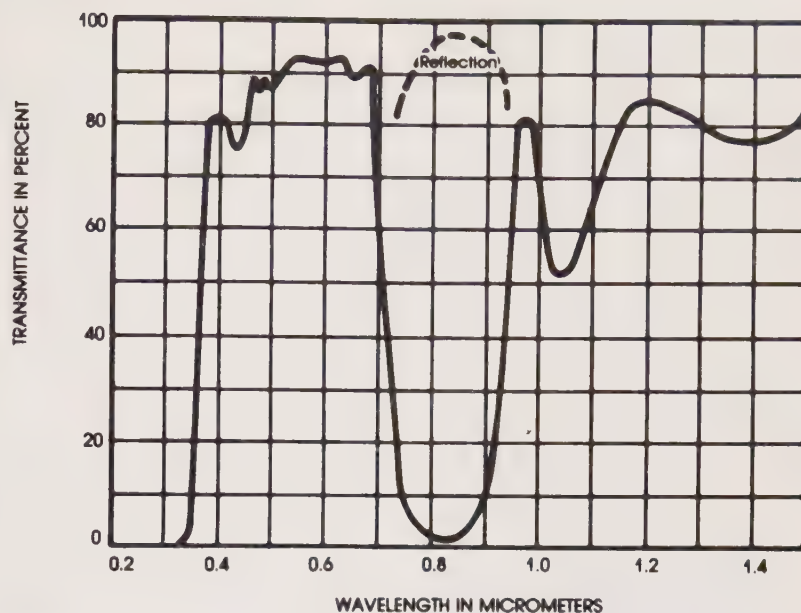
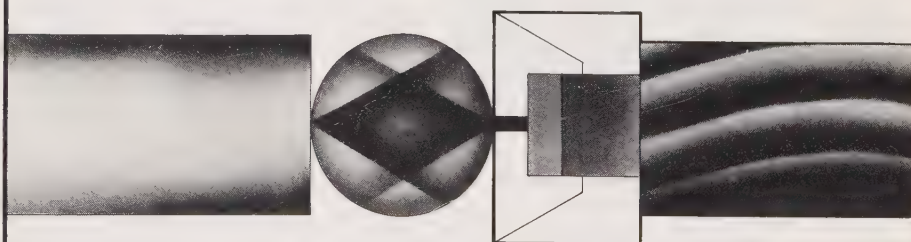


Figure 8.
Spectral reflectance (dashed) and transmittance (solid) of a "hot mirror."

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Specifying Glass Mirrors

The specification of a mirror involves two different areas of consideration: the substrate and the reflective coating.

The substrate choices

The substrate is the physical foundation on which a coating is deposited to achieve a particular spectral performance. In choosing the design specifications of a substrate, you need to examine the operating environment in which the mirror will perform. The temperature stability of the mirror's environment, the physical configuration and the mounting constraints all must be examined closely in order to avoid costly over- or underspecification of the mirror.

Temperature stability affects not only the choice of raw material for a substrate, but also the technique used to mount the mirror. Both of these factors, in turn, affect the optical characteristics (wavefront) of the reflected energy. When the temperature at which a mirror is used increases or decreases, the substrate will expand and contract unevenly, distorting the wavefront, unless the mirror is allowed to temperature-stabilize prior to use. This problem can be partially compensated for by careful choice of substrate material. Table 1 summarizes the characteristics of major glass mirror materials.

Under very stable conditions or where accurate surface figures are not required, optical glasses such as BK-7 and even plate glass can be used as mirror substrates. BK-7 has the excellent transmissive properties needed for back-surface mirrors, but its relatively high expansion proper-

ties usually eliminate it as a mirror substrate.

For less stable conditions, fused silica materials offer excellent expansion stability, but at far greater cost. There are a number of grades of fused silicas, ranging from "Schlieren" grade for use in back-surface mirror applications to commercial grade, which should be used only for front-surface applications. Although the various grades have the same low expansions, the Schlieren grade material can cost more than four times as much as the commercial grade.

Pyrex (TM, Corning Glass Works) is by far the most commonly used mirror substrate, giving reasonably low expansion qualities at low cost. Our experience at Optical Components Inc. is that 60-70 percent of all mirrors we fabricate are made of Pyrex. It cannot, however, be used for transmission.

Zerodur (TM, Schott Glaswerke, Mainz) is a relatively new glass-ceramic that far exceeds the expansion stability of fused silicas. As a front-surface substrate material, it is unsurpassed, and its coefficient of expansion is near zero. However, Zerodur has relatively high scatter and absorption, limiting its use as a back-surface mirror material.

Back- or front-surface?

Back-surface designs utilize both the front and back surfaces of a mirror. The front surface acts as a window in the case of a flat surface or as a correcting lens in the case of a spherical or aspheric curved surface (Figure 1). For this type of design, the homogeneity of the substrate

material must be considered. Back-surface mirrors offer better protection of the reflective coating with extremely hard overcoats and/or paint applied to the coated surface (see Figure 1). On the negative side, they require grinding, polishing and anti-reflection coating of the first surface, and will require expensive fused silica material when used under unstable temperature conditions.

Optical figure and clear aperture

"Optical figure" is the term used to describe the deviation of a reflectance surface from its ideal design value, and is expressed in wavelengths of light. Common wavelengths used to determine the optical figure include 632.8nm (from a HeNe laser), 589.3nm (from a sodium source), and 546.1nm (from a mercury source); one wave of 546.1nm light corresponds to about ten millionths (0.000010) of an inch.

The degree of precision needed in the optical figure has a critical effect on costs. A surface figure of three waves or more is relatively easy to fabricate and therefore inexpensive. As the figure requirements become more demanding, the cost escalates rapidly, especially at accuracies beyond $1/5$ wavelength. Note that figure qualities better than $1/20$ wave may be difficult to measure without having access to an expensive computer-aided digital interferometer.

The "clear aperture" is the area of the mirror actually being utilized and should be specified to be the area over which the optical figure and scratch-and-dig specifications are to apply. In most cases, the specifier should avoid clear apertures of

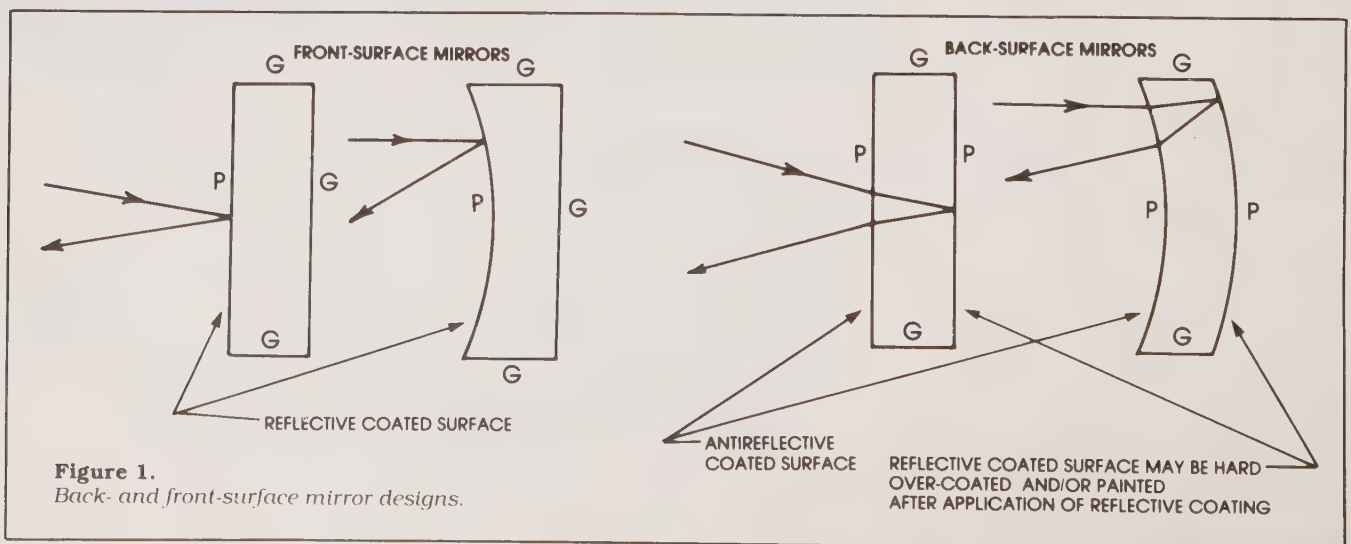


**TABLE 1.
COMPARISON OF
SUBSTRATE MATERIALS**

	Coefficient of Expansion (cm/cm°C) (20°C-300°C)	Back Surface Applications?	Approximate Cost 2" dia x 1/2" th. blank/100
BK-7	83×10^{-7}	Y	\$ 1.75 ea
Pyrex	32×10^{-7}	N	2.00 ea
"Schlieren" Grade Fused Silica	5×10^{-7}	Y	53.00 ea
Commercial Grade Fused Silica	5×10^{-7}	N	13.00 ea
Zerodur	0.5×10^{-7}	N	6.00 ea

90 percent or more. It is extremely time-consuming to correct the optical figure out to the edges of a substrate and thus will drive up costs. If you only intend to use a small central area of the mirror and can limit clear aperture to 80 percent or less, you will save a considerable amount of money.

Matters of shape

The simplest, least expensive, and most common configuration for mirrors is the circular disk. Virtually all other shapes can be considered, but each machined surface added will involve time-consuming direct labor operations that will increase costs rapidly. Substrates with large beveled edges or wedge shapes should be avoided not only because of the labor-intensive shaping involved but also because the optical figure can become distorted due to flexing of thinner edges during the polishing process. Holes are also an expensive addition to a mirror and should be avoided unless they are absolutely necessary.

In many cases, odd shapes in medium- to high-quantity production runs can be made from molded pressings of materials such as Pyrex and BK-7, saving considerable cost, especially if non-mounting and non-polished surfaces can retain their molded finish. The tolerances of molded surfaces will have to be loose in comparison to ground or polished surfaces because molded surfaces retain relatively large surface irregularities, making dimensional checks more difficult.

The aspect ratio, which is the ratio of the diameter (or largest dimension) to the thickness, is also a very important factor in mirror specifica-

tion. Any ratio greater than 6:1 should be reserved for non-precision mirrors requiring no better than half-wave surface figure. This becomes even more important as the major dimension increases since supporting the substrate requires greater care to avoid warping during the grinding and polishing process, especially when dealing with optical figures of 1/4 wave or better on mirrors of six inches in a major dimension or larger.

Aspect ratio also plays a part in the ability of the substrate to maintain its required surface figure during bonding or mounting. Once again the physical shrinking of a bonding agent or the pinching or uneven pressure of a mount can easily warp a thin mirror. The cost of a thicker substrate is usually insignificant in comparison to the direct labor and time involved to correct the figure of a thinner mirror.

Bevels and chamfers help protect the substrate against chipping and fracturing during the fabrication process and also during minor mishandling accidents. Unless a bevel is going to interfere with a clear aperture or assembly location surface, there is no reason to put tight tolerances on it. In general, bevels should follow the MIL-SPEC guidelines of 0.005 to 0.020 inch, although larger bevels offer more protection. For substrates greater than six inches in major dimension, bevels of 0.030 or more should be considered. Because of the extreme brittleness of glass, sharp glass edges should be avoided if at all possible — they will tend to lead to high reject rates from chipping.

Almost all optical surfaces contain small imperfections in the form of

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scratches and digs that are the result of the processes used to shape and polish a substrate. MIL-O-13830 details the industry-accepted measurement standard as being the width of the scratch in microns and the diameter of the dig in hundredths of a millimeter. Thus, a 60-40 specification would allow a scratch 60 microns wide and a dig 0.4mm in diameter. Most vendors maintain glass masters with standard scratches and digs on them to allow direct visual comparisons under diffuse light.

A scratch-dig specification of 60-40 is most commonly used for precision mirrors, with 80-50 applied to commercial-quality mirrors. Typical surfaces used with lasers will carry 10-5 or 20-10 specifications. Quality suitable for lasers requires much closer inspection, usually better than MIL-SPEC. In these cases, high-intensity light sources and microscopes must be utilized to inspect for very small flaws. Any special inspection requirements should be spelled out on the specification drawing and will result in higher costs.

Final cost and volume

The cost differential between a high-volume-production part and a prototype can be anywhere from 100 to 1000 percent. High to medium volume means that precision tooling can be used to fabricate parts, making them less expensive. However, the customer usually pays for tooling development and production costs via non-recurring charges. Most component fabrication houses welcome participation in the design and development of such tooling for high-volume jobs.

For odd shapes requiring tooling, the unit cost is reduced as large

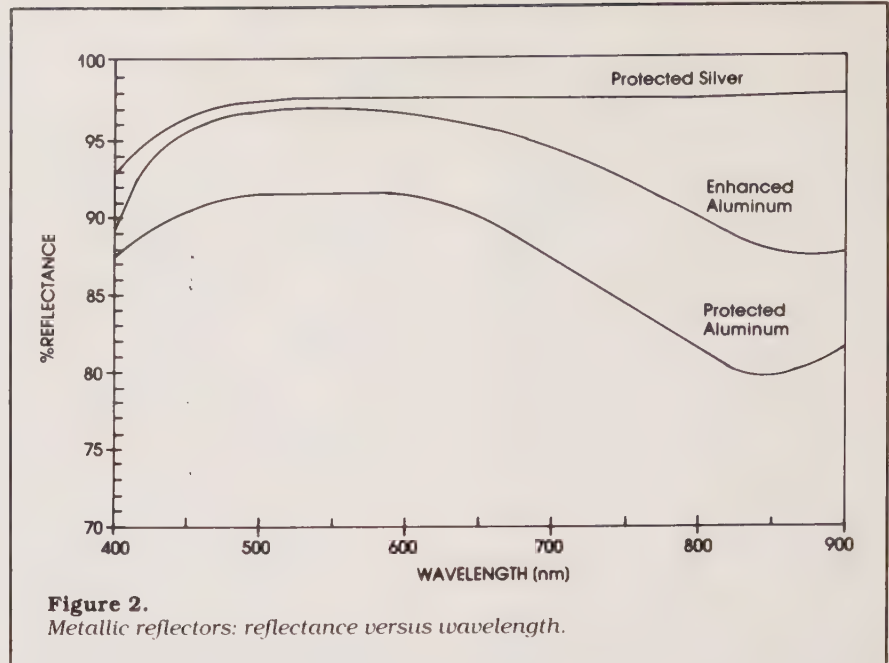


Figure 2.
Metallic reflectors: reflectance versus wavelength.

numbers are ordered. Overall, the key to mirror specification is to reduce the design to the simplest possible shape and lowest number of sides. Obviously, the substrate having many machined faces will not realize the same percentage cost savings as a round disk shape, no matter how large the order.

Metallic reflectors

The most common reflective coating is the first-surface protected aluminum mirror (see Figure 2). Depending on the protective overcoat, this mirror can give good reflectance from the ultraviolet through the infrared, and will also withstand gentle handling and cleaning. As a rule, silicon monoxide and magnesium fluoride are used to protect the aluminum. The cost of this coating is rela-

tively low due to the inexpensive equipment used to produce it.

For higher reflectance, the bare aluminum can be overcoated with two or more dielectric layers. However, the higher reflectance is exhibited over a limited wavelength region — the visible spectrum. Outside this region, the reflectance will fall to values that are considerably less than those of protected aluminum. Although durability is usually better than that provided by protected aluminum, you should exercise care in handling and cleaning. The cost of "enhanced" aluminum is usually higher than that of protected aluminum.

For even higher reflectance, silver is frequently the choice. Due to its reflectance of greater than 96 percent and a broad bandwidth of 0.4-10 mi-

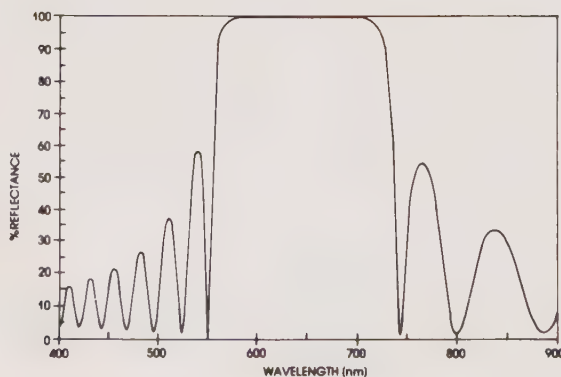


Figure 3.
All-dielectric laser mirrors: reflectance versus wavelength.

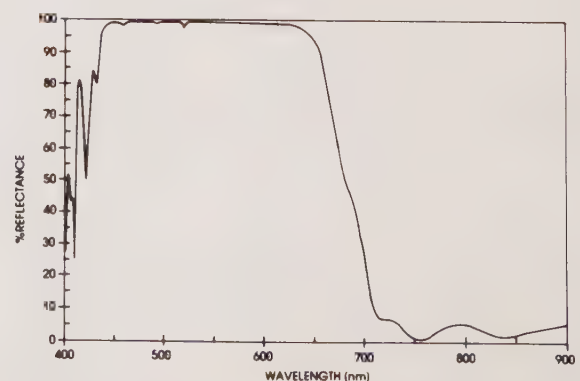


Figure 4.
"Cold" mirrors: reflectance versus wavelength.

MIRROR SPECIFICATION CHECKLIST

Substrate Specifications

Material

Consider temperature stability, optical figure, aspect ratio and if used as a front- or back-surface mirror.

Physical Dimensions

Diameter or Dimensions _____ $\pm$

Thickness _____ $\pm$

Bevels _____

Consider aspect ratio

Optical Figure (in wavelengths)

Specify test wavelength _____

Scratch and Dig (cosmetic defects)

Clear Aperture

Coating Specifications

Spectral Performance

Reflectance _____ %

Bandwidth _____

Angle of Incidence

Degrees _____ $\pm$ _____ $^\circ$

Polarization

"P", "S" or Random _____

Environmental Specs

MIL-SPEC- _____

Laser Power Damage Resistance

W/cm² _____

pulse width _____

repetition rate _____

crons, it has replaced aluminum mirrors in a number of applications. Nevertheless, producing a first-surface silver mirror that is as durable as an aluminum mirror is difficult. Silver does not adhere readily to most substrate surfaces, and it tarnishes easily if not well protected from atmospheric exposure. Although recent advances in substrate cleaning and vacuum evaporation techniques have mitigated these problems to some extent, they can still torment the optical coater. What's more, first-surface silver mirrors will cost more than aluminum mirrors.

Silver is also the most commonly used reflector for a second-surface mirror. In this configuration, the silver film can be adequately protected by overcoating with a "hard" metallic layer such as Inconel. The composite coating is often painted to completely seal the silver from atmospheric exposure.

The all-dielectric reflectors

The other major type of reflective coating uses only all-dielectric materials in its construction. These have reflectances that approach 100 percent and durability that surpasses that of metallic films. Still, the high reflectance is available over a very

limited wavelength interval. Since these reflectors are used primarily in laser applications, reflectance at wavelengths outside a narrow range is usually unimportant (Figure 3).

Because the all-dielectric coating transmits those wavelengths that are not reflected, it is much more versatile than the total reflector. It can also be used to separate various portions of the spectrum: A "cold" mirror, for example, reflects the visible spectrum and transmits the near-infrared (Figure 4).

As a rule, the cost of all-dielectric reflectors will be higher than that of metallic reflectors. Sophisticated equipment is needed to control the process, and since the all-dielectric coating can consist of many layers, fabrication time, comparatively speaking, can be lengthy.

This is the most important specification of any coating, and for a mirror, this specification should include the wavelength interval, or bandwidth, and the reflectivity. Consultation with a good thin-film engineer is always advisable to avoid specifying a spectral performance that is physically impossible.

The cost of a coating is usually directly proportional to its difficulty, and the more difficult a coating is to produce, the higher the rejection

rate and, consequently, the cost. It is always a good idea to contact the vendor to see whether or not this might apply.

Thin-film coatings are usually designed to perform optimally at a specific angle of incidence. However, if a coating is to be used at other angles, you should include that fact in the specification. Note, too, that all-dielectric coatings are generally much more sensitive to changes in the angle of incidence than are the metallic coatings.

At angles of incidence other than normal, it is important to include the type of polarization that the spectral performance applies to. If this specification is not included, the vendor will assume that the polarization is random in nature, which can result in very costly delays.

Laser damage specification is usually given in watts-per-square-centimeter and should include pulse length and repetition rate. Because very few coating houses have the necessary testing equipment, it is a good idea to obtain samples for testing before ordering. Users of large quantities of laser-damage-resistant optics should ask their vendors to supply samples for testing on a regular, say quarterly, basis. Even small changes in test results should be brought to the attention of the vendor without hesitation.

Clear aperture and bevel

Other factors to consider in specifying the coating are the clear aperture and the protective bevel. The clear aperture must allow for coating jig marks, and specifying a clear aperture that is very close to the edge of a substrate may necessitate the use of custom tooling. The protective bevel can have a direct bearing on yield fallout rates. The vacuum deposition process often requires that the substrate be rotated rather quickly at temperatures approaching 300°C. In this type of environment, a substrate with a very small or no protective bevel will frequently be chipped.

Every coating run should include a spectrophotometric chart, and most optical coating houses have the equipment necessary to perform spectrophotometric testing with a reasonable degree of accuracy. Finally, environmental tests, if specified, should also be included, along with the monitor samples, and there should be some means to reference each part to a specific run.

Dale Josephson
Steve Brazelton
Optical Components Inc.

Diffraction Gratings

Diffraction gratings are optical elements, either plane or concave, whose surfaces are modulated with a highly regular groove or slit pattern. The elements can be reflecting or transmitting.

For large-scale application of gratings to spectrometric instruments, a crucial development was the discovery (1950) that one can make replicas with optical properties that are indistinguishable from those of the master. A plastic casting process preserves the entire 3-dimensional surface geometry. This made gratings a production item, almost completely replacing prisms as the principal dispersing element.

Lasers and modern photoresists made it possible to carry out an old idea of Michelson's (1927): to generate gratings by exposure to interference fields of collimated, coherent light beams. Such gratings, sometimes made without collimating optics, are usually described as holographic, although "photoresist" or "interference" grating would be more appropriate. Freedom from limitations inherent in ruling engines leads to reduction in ghosts and stray light, useful in some applications where reduced efficiency is not a problem. Since grooves are un-

der optical rather than mechanical control, they may be given a certain degree of curvature and unequal spacing designed to improve the sometimes poor imaging conditions of concave gratings (astigmatism). One obtains a relatively broad spectral range of medium efficiency.

Scanning spectrometers, now much more widely used for spectral analysis than spectrographic systems, usually take advantage of the astigmatic imaging and simple wavelength control inherent with plane gratings used in collimated light.

Selecting a grating

Choice of grating size is usually dictated by the desired system throughput, a function of source, detector, resolution and the desired data acquisition rate. In some cases, resolution requirements determine the minimum acceptable aperture of the system.

At a given wavelength, the angular dispersion of a grating is a function only of the angles of incidence and diffraction. Once these have been determined, the corresponding groove spacing becomes a function only of the order in which the grating is to operate. Most gratings are used

in the first order, as this minimizes difficulties with overlapping wavelengths and gives high efficiency over a wide range. However, many systems operate successfully in the second or even higher orders.

In the special case of echelle gratings, orders below 5 are rarely used. Some kind of filtering becomes necessary to prevent order overlapping, unless one has a narrow band source like a laser. Filtering may take the form of wavelength cutoff by the detector, bandpass filter, or cross-dispersion with another grating or prism. The result is a high-resolution, high-dispersion system with compact data presentation.

Efficiency and blazing

In all diffraction gratings, the fraction of monochromatic incident light that ends up being diffracted (known as grating efficiency) varies with wavelength. The physics of the interaction between light and the grating surface is determined primarily by four variables: the ratio of wavelength to groove spacing (λ/d); the shape of the grating groove; the nature of the material of the grating surface; and the angle of incidence.

In most spectrometric situations, there are limitations in light source,

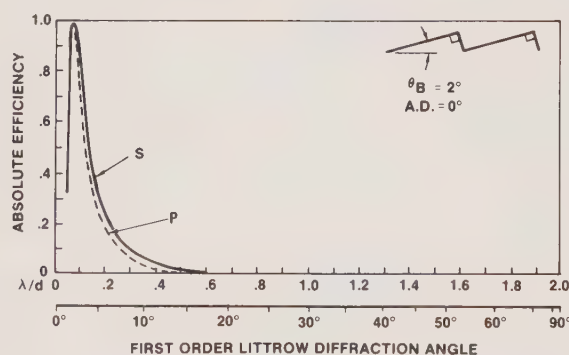


Figure 1.

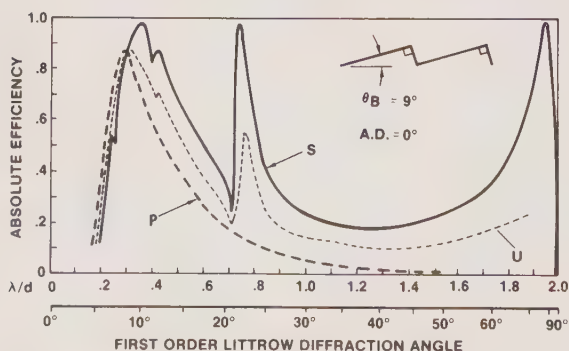


Figure 2.

Figures 1-10.

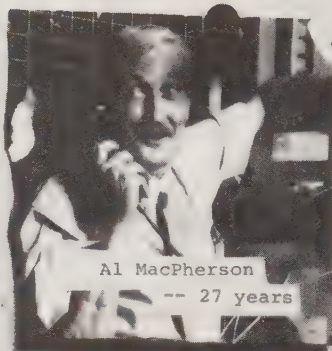
First order theoretical efficiency curves for gratings of various blaze angles θ_B as shown. Separate curves are shown for unpolarized light (U) and light polarized parallel (P) and perpendicular to the grooves (S). To make the curves universal, we plot them as a function of wavelength (λ) to groove spacing (d). Corresponding Littrow diffraction angles are also given. Figures 1-6 are for the Littrow condition, with the angular deviation (AD) zero (see page 240 for Figs. 3-6). Figures 7-10 (see page 242) are a similar set of efficiency curves for perfectly conducting surfaces, except with sinusoidal shaped grooves with progressively increasing depth modulation.

How do you track down The Gratings People?

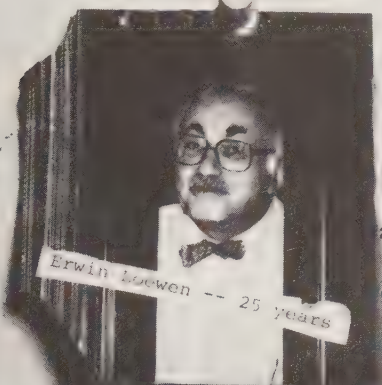
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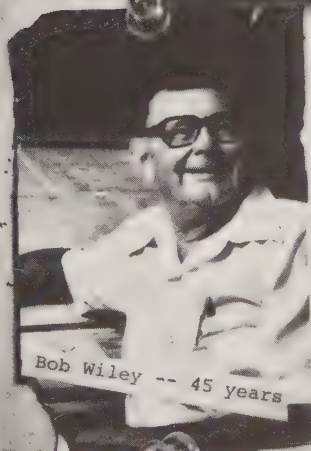


Erwin Loewen -- 25 years

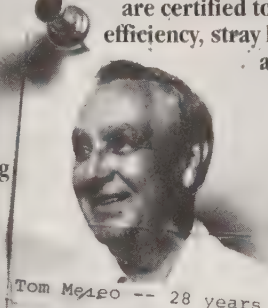
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detector, or both. This makes it highly desirable to pick a grating whose efficiency is optimized, which is not difficult to do once the fundamentals are understood.

Theoretically, the most efficient groove shape for any grating is a right angle triangle. The inclination of its hypotenuse is called the blaze angle, because it determines the direction in which a diffracted beam has its greatest efficiency. Such gratings are termed blazed. Other groove shapes, especially the sinusoidal groove characteristic of photoresist gratings, are also useful and, under certain special conditions, exhibit efficiencies comparable to those of blazed gratings.

By starting with infinite conductivity (i.e., perfect reflectors) the efficiencies can be plotted against the dimensionless ratio λ/d . The Littrow or autocollimating mount will be used for simplicity. Effects of departure from Littrow and the role of finite conductivity will be discussed separately. The highest-quality ruled gratings have been found to approach theoretical performance remarkably well. How these theoretical calculations hold up in practice will be described.

The six blazed grating families

Littrow mounted infinite conductivity surface blazed gratings are completely characterized by their

blaze angles. One can classify six blaze angle regions, so an example of each provides a very good overall insight into grating efficiency behavior. These are the very low (1 to 5°), low (5 to 10°), medium (10-18°), special low anomaly (18-22°), high (22-38°) and very high (38-70°) blaze angles. To present the efficiency curves in family form, we show them plotted as a function of the dimensionless ratio wavelength (λ) to groove spacing (d). This is converted to wavelength units by multiplying by d . To provide an additional frame of reference, the corresponding first-order Littrow angles are also shown.

Figure 1 shows the theoretical efficiency of a grating with the very low blaze angle of 2°. Polarization effects are negligible. The efficiency peak is always exactly where $\lambda/d = 2 \sin \theta_B$, and where θ_B is the blaze angle and approaches 100%. For comparisons between gratings, it is convenient to note the wavelength region over which the unpolarized light efficiency (i.e., the average of S and P curves) exceeds 50%. In this case, it is obtained over a band from $\frac{2}{3}$ to $1.8\lambda_B$, where λ_B , the blaze wavelength, is given by $\lambda_B = 2d \sin \theta_B$.

In the low (5-10°) blaze angle region (Figure 2), polarization effects begin to be observable. Rayleigh pass-off anomalies are consistently strongest where the -1 and +2 orders pass off, which for Littrow

mounting occurs when $\lambda/d = \frac{2}{3}$. The S-plane efficiency peak always occurs at the blaze angle, as one can see from the Littrow angle scale derived from the λ/d values. The P plane peak is typically lower, and occurs at a shorter wavelength. The 50% minimum efficiency is met from $\frac{2}{3}$ to $1.8 \lambda_B$ as for the previous grating. A second S-plane efficiency peak occurs when the diffraction angle reaches $90 - \theta_B$, but is observed in practice only with steeper blaze angles, because its realization depends on geometrical perfection of the groove, not only on the blaze face, but on the steep side as well.

As one would expect, the medium blaze region (10-18°) shows stronger polarization effects (Figure 3). The unpolarized curve is shown here as a reminder of its simple derivation from S and P data. The 50% range shifts to slightly longer wavelengths, from 0.72 to $2.0 \lambda_B$.

18-22° blaze-angle gratings (Figure 4) are unique in that they lack strong anomalies over the region where they are normally used. This is because the strong primary pass-off anomalies would take place just where the blaze peaks. These gratings also exhibit the lowest P-plane efficiency peak (80%) of any blazed grating. The range for 50% efficiency again moves up slightly, from 0.75 to $1.9 \lambda_B$, with little bandwidth variation.

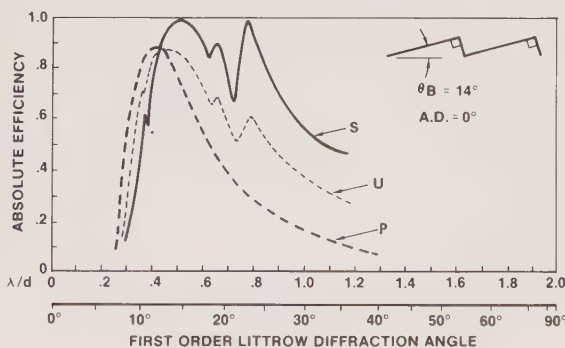


Figure 3.

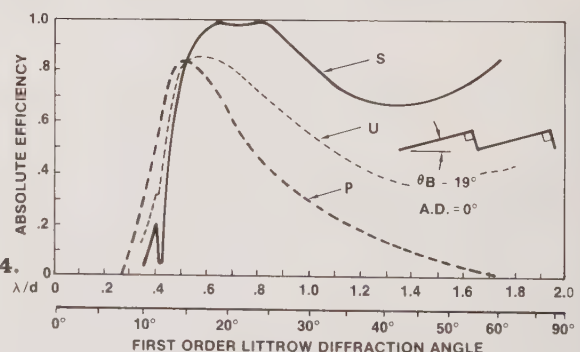


Figure 4.

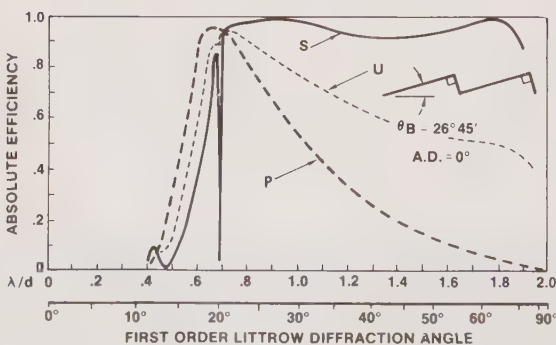


Figure 5.

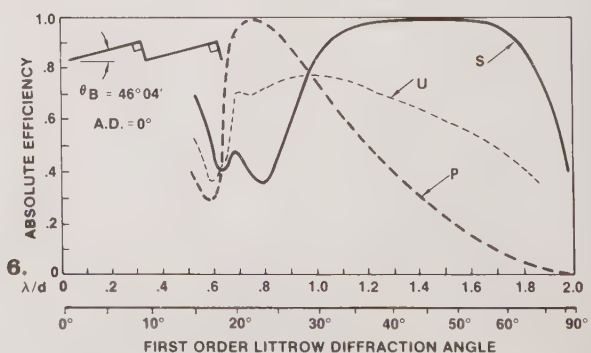


Figure 6.

Optics



Prisms—Plano-Parallel Surfaces
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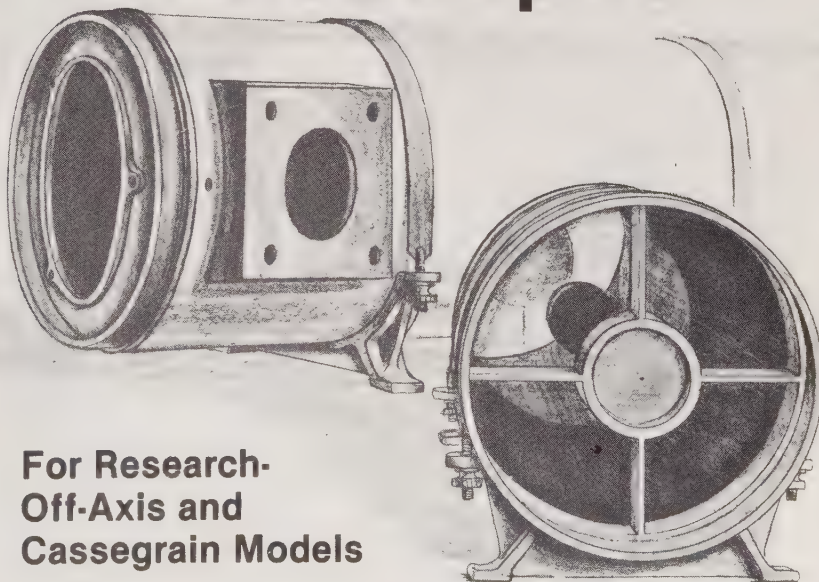
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High-blaze-angle gratings ($22-38^\circ$, Figure 5), are widely used despite the strong Rayleigh anomaly near $\lambda/d = \lambda_0$. Its practical effects are attenuated by the high P-plane peak that occurs at the same wavelength. The broad bands of extremely high S-plane efficiency are frequently taken advantage of when such gratings are used as laser end mirror tuning elements. The second S-plane peak observed at the complement to the blaze angle is used when very high dispersion is desired. It is obtainable in practice only on exceptionally perfect rulings. The 50% minimum efficiency band extends from 0.6 to nearly 2 times the blaze wavelength, the widest of any grating, but the high end is not always usable in practical configurations because of the large diffraction angle.

Very-high-blaze-angle gratings ($34-64^\circ$) have rather peculiar efficiency curves (Figure 6). In practice, they are rarely used in first order, although occasionally the very high P-plane efficiency has useful application. The high end of this range (48° or more) are often termed echelle gratings, and are typically used in orders from 5 to 100.

Except for laser wavelength tuning, gratings are never used in pure Littrow mounting. Monochromators

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usually operate with fixed angles between the incident and diffracted beams, which may vary from 5 to 70°, occasionally even more. The lower the blaze angle, the smaller the penalty for this departure.

Finite conductivity of metals

The effect of finite conductivity on the behavior of real gratings depends not only on the wavelength region, but also on the blaze angle. When the latter is small, the only effect of finite conductivity is to reduce efficiency simply by the reflectance of the metal. This is useful to know, because most ultraviolet gratings, both plane and concave, operate in or near the scalar domain.

In the electromagnetic domain, the role of finite conductivity is convoluted with blaze angle and wavelength. This can give rise to anomaly shifts and in the UV region even generate new ones, in addition to the expected reductions in reflectance.

Behavior of sinusoidal grooves

When groove-shape is sinusoidal, the efficiency behavior is controlled by the modulation h/d , when h is the peak-to-valley light of the groove. Four domains can be distinguished. When $h/d \leq 0.05$, we are in the scalar domain (Fig. 7), where the maxi-

mum efficiency is 33.8%, and will occur at a wavelength of $3.4h$. The low modulation region, when $h/d \approx 0.15$, has a much wider span of use, with a fairly uniform but low efficiency (Fig. 8). Medium modulation gratings, where $h/d \approx 0.25$, are less useful at smaller values of h/d or diffraction angles, but in return are more efficient at higher ones (Fig. 9). High modulation gratings, as in Figure 10, where $h/d \approx 0.36$, show efficiency behaviors virtually the same as Figure 5, both in theory and practice.

Concave grating efficiency

For diamond-ruled concave gratings, the blaze angle will vary across the surface due to the curvature of the blank. The result is reduced blaze peaks and broadened range of wavelengths. Holographically produced concave gratings will have uniform behavior over their entire surface, of special importance when they have to operate in the scalar domain typical of UV systems.

Grating overcoatings

The uniquely broad reflectance curve of aluminum has made this the preferred grating material. In the vacuum UV region, below 1600Å, its reflectance is seriously degraded by the normally harmless thin layer of

aluminum oxide. If aluminum is fired rapidly, and quickly overcoated with a thin layer of MgF_2 , its properties are preserved to 1100Å. Gold has useful reflectance in both the very short wavelength region ($<1000\text{Å}$) and the entire infrared region; it can be used to overcoat an aluminum grating, or made as a primary gold replica. Osmium, exhibiting twice the reflectance of platinum at 600Å, is frequently used in the XUV.

Dielectric coatings of optical thickness ($\sim \lambda/4$) usually degrade grating performance because of complex guided-wave effects on a modulated surface.

Blank materials

For most applications, high-grade optical glass is an excellent substrate for gratings; but for larger sizes and unusual thermal environments, it is important to select low expansion materials such as fused silica or Zerodur®.

For gratings used in high-energy environments, especially with molecular lasers, gratings must be good conductors of heat. This can be accomplished by replicating onto solid copper, rather than glass substrates. When even this fails, as in the high-power lasers, the only recourse is

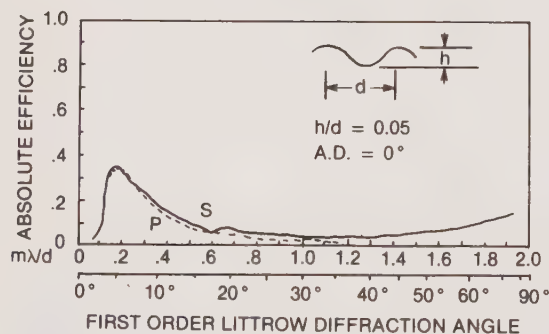


Figure 7.

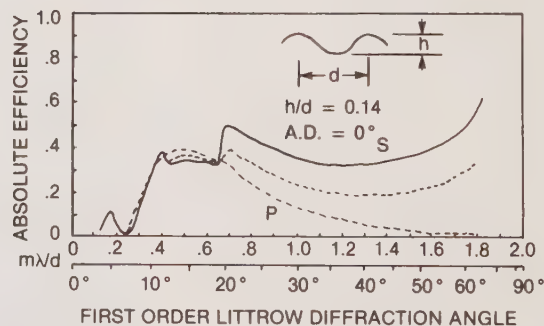


Figure 8.

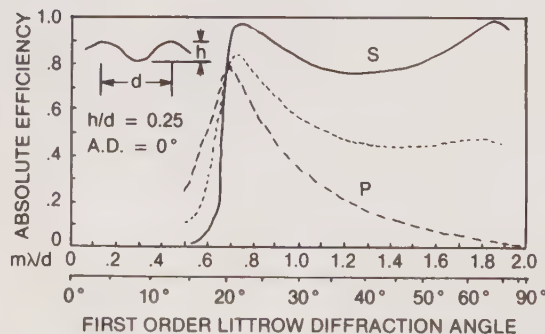


Figure 9.

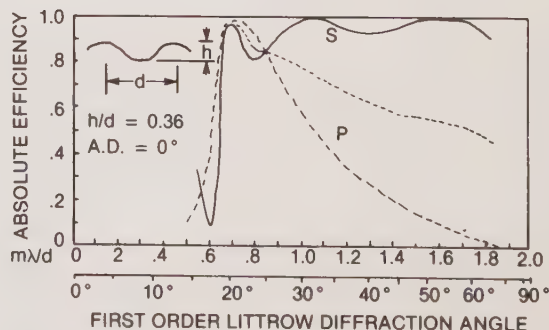


Figure 10.

the use of special gratings with grooves cut directly into a metallic blank.

Transmission gratings

Transmission gratings are used whenever a camera or telescope must be converted into a spectrograph. Frequently, this involves the study of self-luminous objects such as stars, but an illuminated slit can also be used. Transmission gratings differ from reflection gratings, mainly in the absence of an aluminum surface coating. Lack of metal also leads to absence of Woods and resonance anomalies, and minimal polarization effects. Spectral range is limited by the availability of transmitting materials, from 0.22 to 1.0 μm , and diffraction angles are somewhat restricted by internal reflection effects to approximately 35°. Groove frequencies rarely exceed 600/mm. In principle, any reflection grating can be made into a

transmission grating. As a rule, it will be blazed at about $\frac{1}{3}$ the wavelength of the reflection equivalent.

The traditional demand for spectroscopic devices that give higher resolution and dispersion than ordinary gratings, but have a greater free spectral range than a Fabry-Perot etalon or a reflection echelon, was met by the echelle grating, first suggested by George R. Harrison of Mass. Institute of Technology. Physically, an echelle can be thought of as a compromise between a grating and a reflection echelon. An echelle looks like a coarse grating, except that it is used at such a high angle that the steep side of the groove becomes the optically active facet. Typical echelle groove spacings are 316, 79, or 31.6 grooves/mm, all blazed at 63°26'. Thanks to the high angle, high resolutions can be obtained. Echelles are used in high orders, 5 to over 100, so that some type of order sorting is necessary. Usually this takes the form

of a cross-dispersing low-resolution grating or prism, accompanied by a rectangular type of display, easily adapted to TV-type scanning readout. No other spectrometer approaches this level of resolution over a wide range in a compact volume.

Erwin G. Loewen
Bausch & Lomb

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Neutral Density Filters

Class	Attenuate By:	Types & Characteristics
Vacuum-deposited filters: metallic	Absorption and reflection	Fixed density—Density and transmission value are fixed and constant over the entire filter surface. Linear ND wedge—The density and transmission (film thickness) vary linearly across the filter surface. Circular ND wedge—The density and transmission vary angularly. This type of filter typically has a linear density relationship to radial angle. Step ND wedge—The density and transmission vary across the surface of the filter in discrete density steps. The change is abrupt, with no white light between steps. Metallic ND filters attenuate by both absorption and reflection and can be damaged by high-energy infrared radiation. Also, the ratio of reflection to absorption is not constant with varying density values. Metallic ND Filters can be made with density values from 0.5 to over 6.0. Filters with densities greater than 3.0 are generally composed of two or more filters in series, sealed at the edge and having an air gap between the coated surfaces. Metallic ND filters provide maximum density accuracy and wavelength neutrality range at a moderate price.
Vacuum-deposited filters: dielectric	Reflection, some absorption	Some dielectric materials, such as titanium dioxide, can be used as a coating material for ND filters.
Solid glass ND filters	Absorption, some reflection	Solid glass ND filters attenuate by absorption and some reflection (the reflective loss from the air-glass interfaces). Because they function by absorption, their density value is a function of thickness. They come in two types: fixed density and mechanical wedge. Color glass ND filters are relatively neutral over the visible spectrum (400 to 700nm). Below 400nm and beyond 700nm, their density value increases. Color glass filters are moderate to low in price. This type of ND filter can be used in incident cone angles up to 20° total solid angle without substantial change in density value. At about 50° total solid angle, the density increases approximately 4% because of the increased path length through the absorptive filter at the extreme cone angle. For the mechanical wedge, a relatively thick, fixed-value, solid-glass ND filter is ground and polished with a thickness wedge. Then, a complementary plain glass wedge is cemented to the density wedge. The result is an attenuator whose density varies continuously with position.
Photographic negative ND filters	Absorption, scatter	Fixed density—This type of filter is made by exposing a silver-containing emulsion negative to controlled levels of white light, and then developing it by standard means. Attenuation is by absorption and scatter. The density value is fixed and constant across the filter surface. The range of neutrality is approximately that of the visible spectrum, outside of which the density value changes substantially. The stability of these filters is poor but cost is relatively low. Linear and circular wedge—Negative wedge neutral density filters are made by changing the exposure level across the surface of a silver-containing photographic negative using a gradually moving shutter to control the exposure over the surface. Negative wedges can be made so that the transmission or density varies linearly with dimension or angularly over a circle. Step wedge—The discrete density steps in a negative step wedge are produced by a move-and-stop shutter controlling exposure. Each density step is uniform within the step, and there is no white light between adjacent steps. Once a master step wedge is made, it can be used to expose additional replicas.

Class	Attenuate By:	Types & Characteristics
Specialty ND filters	Absorption, scatter	Wire grids and screens—A filter neutral over a substantial wavelength range can be made with a network of fine wires forming uniform grids or screens. The wires obstruct light, altering the amount of transmission. Unfortunately, the degree of attenuation can change with beam size. If a small diameter beam is incident on a screen with wide wires, the throughput could be affected by the position of beam relative to the wires. With fine wire attenuators, dust could be a problem. Suspended carbon particles—Carbon particles suspended in gelatin form relatively low cost neutral density filters. These filters function by scattering and by some absorption. Their density values can be controlled quite accurately, and the range of neutrality is the visible spectrum. The gelatin surfaces are fragile, and require care in use and handling. Gelatin filters are often laminated between protective glass plates.
Plain Glass	Reflection	Ordinary glass can be used as a neutral density attenuator, if the 8% reflection from the two air-glass interfaces is considered. Eight glass slides or plates in series with an air space between each pair produce a density attenuator with a value of approximately 0.3 (51% transmittance) and neutrality over the nominal transparency range of the glass used.

NEUTRAL DENSITY FILTERS:
OPTICAL DENSITY CALCULATIONS

Optical density is defined as the logarithm to the base 10 of the ratio of the incident light to the transmitted light. That is,

$$O.D. = \log_{10} \frac{I_o}{I_T}$$

where O.D.=optical density, I_o =incident intensity, and I_T =transmitted intensity. Thus, a neutral filter with an optical density of 3.0 yields

$$O.D. = \log_{10} \frac{1}{.001} = 3.0$$

Neutral density filters may be stacked in series to produce different and intermediate density values. The total density of a stack is equal to the sum of the individual filters' densities. The total transmittance of a stack is equal to the product of all the individual transmittances.

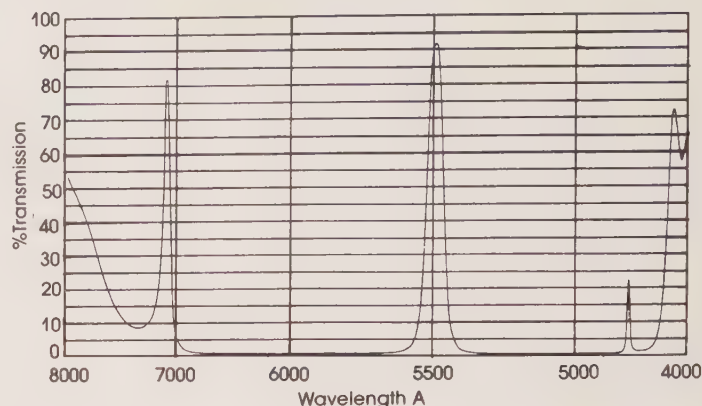
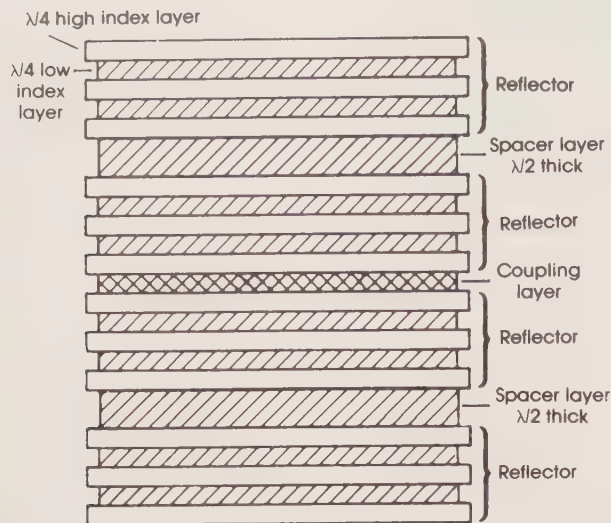
It is very important to note that adjacent metallic neutral density filters in a series should not be parallel. Parallelism may cause multiple surface reflections to combine on the throughput light path, increasing the transmittance or decreasing the density.

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Physitac Corp.

Typical Holographic Optical Elements

	Fringe Type	Fringe Pattern	Material
Wideband Applications			
Plane Diffraction Gratings	Surface	Straight line	Photoresist
Concave Diffraction Gratings	Surface	Hyperbolic (requires design)	Photoresist
Fiber Optic Multiplexer	Surface/volume	Curved	Photoresist
Laser Applications			
Holographic Notch Filter	Volume	Straight line	Dichromated Gelatin
Hologon Scanners	Surface/volume	Curved or Straight	Dichromated Gelatin or Photoresist
Beamsplitters	Surface	Straight line	Photoresist
Head-Up Displays	Volume	Curved	Dichromated Gelatin
Microposition Encoders	Surface	Straight line	Embossed Mylar

Interference Filters



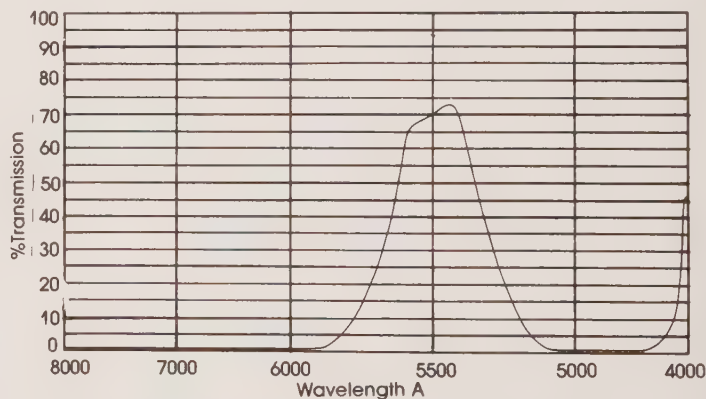
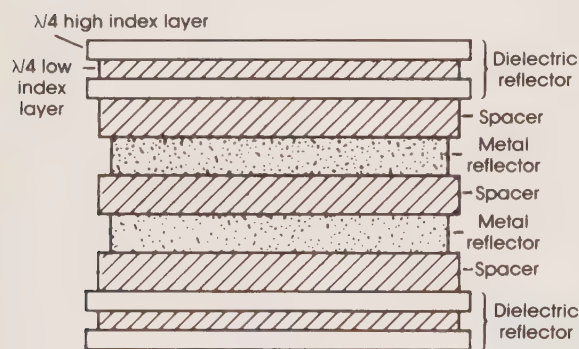
To improve the performance of the classic Fabry-Perot filter, non-absorbing, all-dielectric, multilayer stacks can be used as reflectors to replace the metal layers. In this case, the bandwidth at a given wavelength for a given combination of dielectrics is logarithmically related to the number of layers in the reflector stack. The thickness of the spacer layer controls the central or peak wavelength.

In the all-dielectric, multilayer filter, the shape of the band may be en-

hanced by repeating the deposition of filter upon itself by inserting a coupling layer between the first and second filter. The figure above shows the structure of a two-cavity filter, along with its spectral plot. Additional cavities can be added by insertion of another coupling layer between the second and third filter. Multicavity design increases the slope of the band, making the transition from peak transmission to maximum rejection more abrupt.

As the plot shows, the all-dielectric

filter is an effective reflector over a limited spectral range. Beyond this range, sidebands of transmission appear on either side of the bandpass and must usually be suppressed. The short-wavelength sidebands can be removed readily by a sharp-cut, long-pass, colored-glass filter cemented to the all-dielectric filter. The resultant composite is completely blocked on the low wavelength side. A totally blocked filter requires a filter to suppress the long side of the all-dielectric filter.



In its basic form, the induced transmission filter combines the best features of the all-dielectric and metal-dielectric-metal Fabry-Perot filters: high transmission and flexible bandwidth control, and absence of long-wave transmission, respectively. A typical structure of the induced transmission filter is shown with corresponding spectral plot.

The apparent thickness of the precisely controlled layers in interference filters is a function of the angle of incidence of incoming radiation. At off-normal angles, the light path

through the deposited layer is changed, and the filter is centered at a different wavelength than it is for normal incidence. For perfectly collimated incident radiation, off-normal angles produce predictable shifts to lower wavelength values — changes in bandwidth and peak transmission are minimal for small incident angles.

The change in central wavelength with angle of incidence is primarily a function of the index of refraction of the spacer layer. For predicting the change in central wavelength, the

term n^* (effective index of the total filter) is used. In addition to space layer index, n^* is influenced by the indices of the layers in the reflector stacks. A low-index spacer layer produces a large wavelength change with off-normal incident angle, whereas a high-index spacer layer produces a smaller change.

The derivation of the effective index of refraction of the total filter (n^*) is given for a high-index-of-refraction spacer layer by

$$n^* = \sqrt{n_H \cdot n_L}$$

For a low-index-of-refraction spacer layer

$$n^* = \frac{n_L}{[1 - (n_L/n_H) + (n_L/n_H)^2]^{1/2}}$$

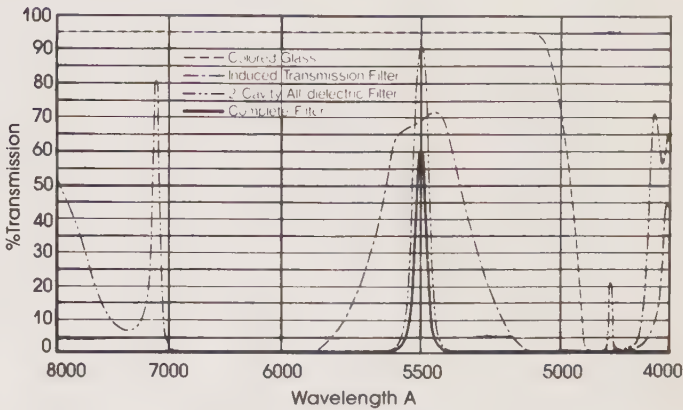
A totally blocked filter combines the all-dielectric filter, the induced transmission filter and a sharp-cut, long-wave-pass, colored-glass filter. In the totally blocked filter, the transmission at any wavelength is the product of the transmissions of each constituent filter.

The complete filter depicted at the right is not intended to represent the majority of bandpass interference filter designs.

where n_L = index of refraction of the low index layers and n_H = index of refraction of the high-index layers.

For the zinc sulfide ($n = 2.2$), cryolite ($n = 1.35$) system, the n^* value

for the cryolite spacer layer is approximately 1.45; and the n^* for the zinc sulfide spacer layer is approximately 2.0 (note that these are experimental values).



INTERFERENCE FILTERS: INCIDENT ANGLE EFFECT

Design parameters for use of optical interference filters are always understood to apply to collimated light, normal to the surface of the filter. For other conditions, correction factors must be applied.

In the "collimated, off-normal incidence" condition, all rays are parallel to each other but off-normal to the filter surface. The central wavelength under these conditions for angles less than 30° is

$$\frac{\lambda_x}{\lambda_o} = \frac{\sqrt{n^{*2} - \sin^2\theta}}{n^*}$$

where λ_o = central wavelength at normal incidence, λ_x = central wavelength at the off-normal angle and θ = the off-normal angle.

In an electro-optical system, the most common off-normal situation has the radiation source incident to the filter surface in either a convergent or divergent configuration. A good working approximation of the effective peak wavelength of the filter can be made in system where the beam intensity is near uniform and the total solid angle is less than 20°.

To calculate the peak wavelength shift for a divergent or convergent light source system, use the maxi-

WAVELENGTH MULTIPLYING FACTORS FOR COLLIMATED OFF-NORMAL INCIDENT ANGLES					
Angle Degrees	Low Index Spacer ($n^* = 1.45$)	High Index Spacer ($n^* = 2.0$)	Angle Degrees	Low Index Spacer ($n^* = 1.45$)	High Index Spacer ($n^* = 2.0$)
0.25	.99999	.99999	10.0	.99280	.99622
0.5	.99998	.99999	15.0	.98394	.99159
1.0	.99993	.99996	20.0	.97178	.98527
2.0	.99971	.99985	25.0	.95658	.97742
3.0	.99935	.99966	30.0	.93867	.96825
4.0	.99884	.99939	35.0	.91844	.95800
5.0	.99819	.99905	40.0	.89637	.94695
7.5	.99594	.99787	45.0	.87303	.93541

mum half-angle. (Don't use the total solid angle indicated in the "wavelength shift expression." The shift will be about half that predicted by the equation.) In practice, filters with 1/2-bandwidths over 30A have insignificant wavelength shifts in convergent or divergent systems with up to 5° total solid cone angle (f/11).

To simplify calculations of wavelengths shift factors, refer to the table. It is intended exclusively for filters using cryolite ($n^* = 1.45$) or zinc sulfide ($n^* = 2.0$) spacer layers.

Example: find the wavelength shift of a filter with a low-index spacer layer ($n^* = 1.45$) and a central wavelength at normal incidence of 5500A used in a 10° off-normal collimated beam. The factor from the table for 10° is .99280, so the wavelength shift can be found as follows:

$$\begin{aligned} .99280 \times 5500A &= 5460.4A \\ \Delta\lambda &= 5500A - 5460.4A = 39.6A \text{ shift} \end{aligned}$$

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Mechanized Alignment Adjustment of Modular Systems

It's getting harder to build military optical systems. While package volumes are shrinking, performance requirements are increasing. Reliability and maintainability are almost becoming fetishes, with environmental requirements (temperature, vibration, shock, and humidity) becoming more stringent and in some cases more difficult to meet. Lasers, in their ever-increasing diversity, now seem *de rigueur*, and exotic infrared materials are in high demand. But one of the most significant trends, from the optical designer's standpoint, is the now-mandatory modularity of optical systems, and with it, the requirement that similar modules be totally interchangeable without realignment.

Some basics: degrees of freedom

The most important adjustment concept is "degrees of freedom," which is simply the number of unique ways a part can move. Everything in the world, light bundles as well as manufactured parts, starts out with six degrees of freedom (see Figure 1): three lateral (usually in the directions of the three coordinate axes X, Y, and Z) and three angular (we'll call them A, B, and C) around these axes. All six must be constrained individually and uniquely in each case for a part to be completely stable; using too few constraints permits unwanted motion, while using too many guarantees stress. There are many cases (such as circular symmetry) where degrees of freedom cease to be important, but none where they go away.

Thus, the number of constraints is a very accurate indicator of both part stability and adjustment requirements. For example, two perfect plane surfaces in contact control three degrees of freedom — one lateral and two angular. If, referring to Figure 1, the planes are parallel to the XZ plane, then movements in Y, A and C are not possible, but movements in X, Z and B are free. This is the case for all flat mounting pads, whether or not there is a screw through the pad center.

The use of three such pads triply overconstrains Y, A and C, and thus guarantees stress, but this is the most common mounting arrangement. As a general rule, we designers always "cheat" when we use three pads in this situation. That is, we keep the pads as small as possible, and the surfaces as parallel as pos-

sible, to make sure that overconstraining does not mean overstressing. The trick is to keep the results of our cheating within the tolerable bounds.

Basically, when adjustments of a part are required within an optical system, you simply need to count the number of degrees of freedom requiring control and then provide exactly that many independent motions. The most common mistake is to make too many adjustments. These adjustments need not even be of the same type. For example, a pair of binoculars needs to be "collimated" — that is, the two field centers need to be moved angularly (A & B) until they are parallel with the hinge axis. To accomplish this, many companies use a pair of eccentric rings around each objective lens, which will permit it to move laterally (X & Y).

Differential expansion and bonded joints

Differential expansion is the other important concept too often not given proper respect in the adjustment and design of optical systems. All materials expand differently, and all of this expansion is nonlinear, making predictions more complex than many designers appreciate. For example, two alloys of the same metal will have

different expansion coefficients, and two materials with the same room-temperature coefficient will not have the same curve of expansion at other temperatures. So provision must be made for an amount of bending or sliding adequate to accommodate the expected motion. If no provisions are made, nature will make its own, and these often don't meet with the designer's approval.

Expansion is one of the three major problems encountered in bonded joints, the other two being shrinkage during the cure cycle and creep over extended periods of time. A lens bonded with a ring of adhesive (such as RTV) into a cell is a candidate for destruction. There are three expansion coefficients working on the lens, and even if the adhesive is flexible, it will get hard enough to cause damage when the temperature drops. To avoid these problems, bonding agents and processes must be selected very carefully.

What to adjust

The cardinal rule here, as in so many other cases, is — keep it simple. Unfortunately, the practice that I seem to find in epidemic proportions wherever I go runs completely contrary to this rule. Designers will give every part six degrees of freedom because,

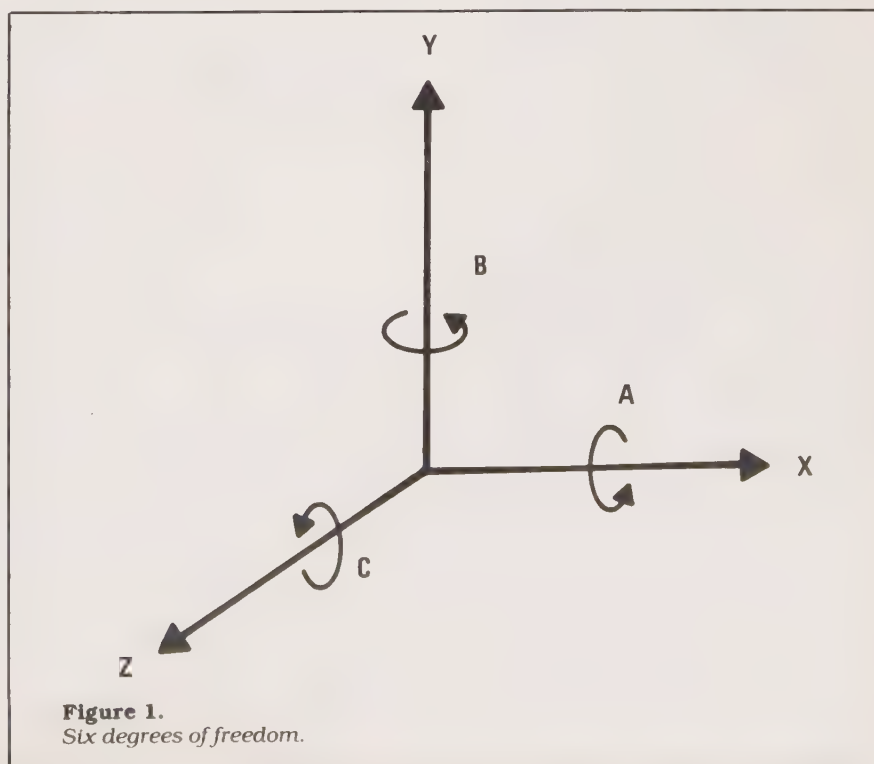


Figure 1.
Six degrees of freedom.

they say, they are not sure how many degrees they will need until they actually build the system. This usually produces a system where (1) some key adjustments are missing ("too difficult to include," they say), (2) other adjustments do not have the required degree of finesse, (3) the excessive adjustments simply cost time during assembly, and (4) the complex parts are less stable than they should and could be.

There are really only two reasons to move any element of an optical train: aberrations and alignment. The one-time relative positioning of the two parts in a cemented doublet, for example, minimizes axial aberrations. Lateral adjustment of the reticle (or equivalent motion) in a rifle scope permits alignment of the scope and barrel. These examples have only two degrees of freedom. By comparison, each element in a complex camera objective has five degrees of freedom that must be controlled. It is a credit to the camera industry that so few parts are required for this task.

Laser systems provide some simple examples of adjustment decisions. Here, four cases will be examined: (1) the beam coming out of the laser; (2) the input to a beam-expanding telescope; (3) the final "boresighting" of the output beam; and (4) laser divergence control.

Laser output — The output from a laser usually has its location and direction specified to very close tolerances for four degrees of freedom (X, Y, A, and B), so four independent motions are needed. These are "low-frequency" adjustments, since they will probably only be worked when the laser is serviced. Therefore, though they can't be permanently bonded, they do not need to be motorized either.

A serious problem here is the question of references. The body of the laser will have pads, pins, rods or other surfaces that presumably define the coordinate system for the exit beam. To be useful, however, these must be converted to an optical reference for the measurement equipment. A little thought here can pay big dividends later. For example, it helps to make pads coplanar and accessible to an optical flat. If pins are used, they should be aligned along the desired beam path, rather than at an angle.

Input to a telescope — The input to a beam-expanding telescope has the same four degrees of freedom as the laser output. The biggest differences will be in references, methods and possible complexity if boresight is combined with telescope alignment.

Boresight — Boresight can usually be defined as the parallelism of two lines or rays. Only two angular degrees of freedom are involved, but accuracy is usually very high — on the order of a few arc-seconds. It may sometimes have to be dynamically adjustable. References are again a problem: "the center of the TV raster" is usually not an adequate description, and pads and pins are difficult to reference optically.

Divergence control — Superficially, laser divergence control is easy: simply adjust the focus of a beam expander. There is one linear degree of freedom, just like a telescope eyepiece. This is simple if it is a one-time adjustment to, for example, the point of "best" collimation. However, if divergence is dynamically variable, boresight must be maintained. This usually means that the mechanical motion and the laser beam must both be aligned exactly to the optical axis of the lenses. Now you have six more degrees of freedom: two angles for the mechanical axis, plus the four previously described for the expander input.

These few examples illustrate some key general principles:

- Count the variables that need adjustment.
- Be complete, but not redundant.
- Consider the frequency with which each adjustment will have to be made.

- Provide exactly the required number of mechanisms to meet the need.

- Finally, be very careful in the selection of your measurement references.

How to adjust

There are more adjustment mechanisms and techniques than there are designers, and unfortunately, many of the really clever ones remain hidden as "company secrets." Here, we list a few guidelines and gadgets that are not as well known as they should be. These will be used to solve some of the cases described in the previous section.

My guidelines are not meant to be comprehensive or in order of importance. Rather, they are factors that I have seen overlooked often enough to be worthy of comment. They are:

(1) Try not to adjust more than two degrees of freedom with any one part. Things get too complex to be stable, and there's usually another way to approach the problem.

(2) Try not to use set screws. There is almost always a better way.

(3) Let bonding agents cure and stabilize before doing any alignment. This may take weeks.

(4) Whenever possible, do not let a film of adhesive separate two parts that must stay in alignment. Hard mechanical clamps are usually much better.

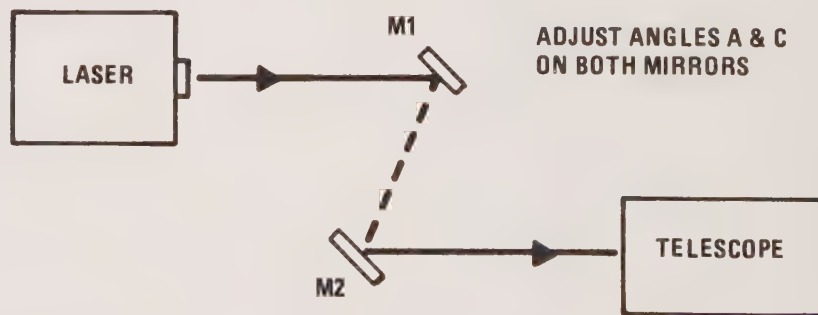


Figure 2.
Mirror alignment.

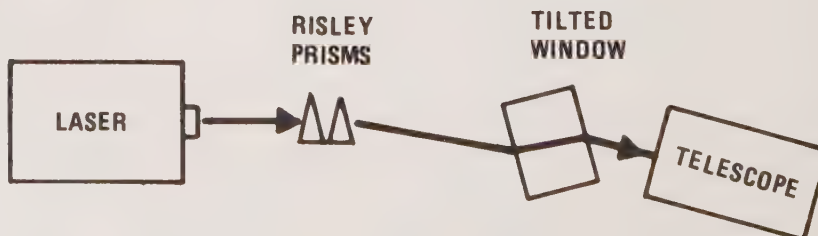


Figure 3.
Prism and window alignment.

(5) Make all adjustments as insensitive as possible. Use long lever arms and high-leverage parts such as Risley prisms.

(6) Avoid stressed metal. Adjustments involving metal flexure will usually move with time as the stresses relieve themselves. Also, working against a spring implies some looseness, which will show up as motion under vibration.

(7) Be careful with push-pull or push-push screw adjustments. They are useful for precise control, but you should find some other way to clamp the part once it is positioned in its place.

Next we will look at five simple parts often used for adjustments, and relate them to the four cases mentioned previously. We will start with the simplest solution to the problem of beam-expander input, which is shown in Figure 2. Since some folds are usually required in such a system anyway, M1 and M2 probably already exist. The beam into M1 is fixed, as is the desired beam path into the telescope. Two-axis adjustment of M1 positions (X and Y) the beam properly on M2, which then aims (A and B) the beam in the required direction. The actual design of the mirror mounts is left to the individual's talents, but note that the motions are very sensitive: with axes in the plane of the mirrors, one degree of mirror motion provides two degrees of beam motion.

Reducing sensitivity

A much more forgiving approach is shown in Figure 3. The problem, again, is the alignment of laser output to telescope input, but two "new"

devices are introduced: a pair of Risley prisms and a tilted window or "aiming cube." If the Risleys are matched 1° wedges with refractive indices of 1.5, 180° rotation of the pair about the optic axis moves the beam a maximum of 2° . This is 180 times less sensitive than the previous case.

Furthermore, none of the other tilts or translations have any material effect on beam direction. The

difficult to design and even harder to make and use, while simpler, more forgiving designs pay dividends at all three stages. Note also that in all of the examples, each part only provided two degrees of freedom.

The binocular objective mentioned earlier (see Figure 4) demonstrates two other often-overlooked techniques: eccentric rings and objective decentration. If the rings are both one millimeter off center, 180° rotation of the pair will move the lens a maximum of four millimeters. This is tremendous leverage, similar to that obtained with the aiming cube, and the rings can be used to adjust anything in a round cell (e.g., detectors or reticles).

The aberrations of most telescope-type optical systems are amazingly insensitive to objective lens decentration. This is therefore a powerful boresighting technique, especially since the objective is on the front of everything where it can be reached after the system is assembled.

Overall, adjustments are a very difficult aspect of the design of military optical systems, but one that could be simplified with relatively minor changes in approach. A good designer will strive for simplicity, and will keep the number, complexity and sensitivity of adjustments to the absolute minimum required for system performance. The number, in particular, can be reduced by the simple expedient of counting the required degrees of freedom and then matching them to adjustments on a one-to-one basis.

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Aeronutronic Div.
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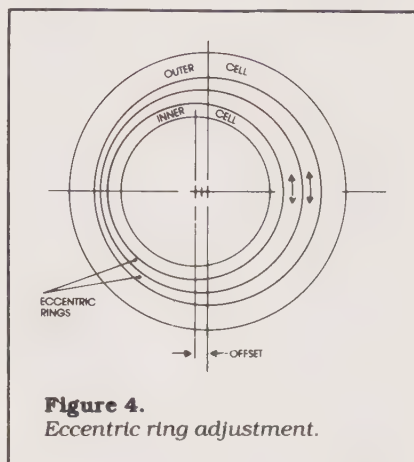


Figure 4.
Eccentric ring adjustment.

aiming cube is similarly insensitive: it cannot affect beam angle at all (assuming parallel surfaces), and a cube one centimeter thick with an index of 1.5 only moves the beam 0.06mm laterally for each degree of rotation. The device can therefore have a very crude two-axis mount and still provide precise positioning of the laser beam on the telescope input.

The principle in this comparison is that highly precise moving parts are

Optical Component Specifications

Designing an optical system involves a great deal more than simply understanding the theory behind optics. There is a production technology involved, and to design efficiently and economically, it is important to understand the capabilities of the optical shop and how the various specifications involved in ordering and designing the components for a system will interact.

To the novice or casual user of optics, the acquisition of an optical system can be a very difficult experience. Failure to understand the ground rules can result in unnecessarily high cost, late delivery or impossibility of execution, to name a few of the consequences.

The best method of avoiding this is an early consultation with an optics vendor or designer. A wide range of experts is available: those who only design; those who will design and furnish prototypes; and large organizations that will design, prototype and mass-produce the final system.

Optics is not like electronics. There are no breadboards that can be fixed up in a few minutes with a soldering iron if the frequency response isn't up to spec. Once a lens is designed and built (correctly) there is only an infinitesimal chance that tinkering with it will significantly improve its performance. An optical system can often be mocked up out of stock components — which were probably designed for another type of application entirely — but if a high level of performance is needed, a system specifically tailored for the application is usually necessary.

Extreme care should be taken to specify only what is necessary and to allow the vendor/designer as much freedom as possible to balance and compromise in achieving the necessary ends. If at all possible, specify only what can be tested — although bear in mind that an indirect test of a characteristic is often as good as a direct test. Be sure that the characteristics given tolerances are those that actually do affect the functional performance of your system.

General considerations

One of the most difficult areas of optical engineering for both novice and expert is determination of the tolerances to be applied to specifica-

tions that are sent to the shop. On one hand, an overly generous set of allowances may lead to the failure of a well-designed system; on the other hand, tolerances that are too severe waste time and money for all concerned. In optics, this situation is further complicated by two factors: (1) the tremendous range of tolerance sizes (e.g., from surface regularity tolerances in tens of nanometers or microinches, to thickness variations in millimeters or hundredths of an inch); and (2) the fact that, if enough time and money are available, almost any conceivable degree of accuracy is attainable.

Tolerances must be tight enough to ensure the proper functioning of the overall system; however, tolerances "add" statistically, and frequently you can take advantage of this to allow larger tolerances than those that seem to be the maximum permissible. A relatively modest effort expended in the choice of tolerances can pay good dividends.

You must take into account the characteristics of an optical shop in specifying tolerances. First, every characteristic and dimension should be specified; the wide range of tolerance values will indicate why "box" tolerances are almost never used in optics. Secondly, the tolerances should be geared to the capabilities of the shop; dimensions that are difficult for the shop to hold should be loosely specified. Thirdly, you should look for ways in which the effect of a dimensional variation can be minimized; for example, the effect of a thickness variation may be vastly different, depending upon which surface of the element the mounting design "fixes" with respect to the balance of system, and which surface is allowed to "float."

Surface quality

The "quality" of an optical surface is an indication of the finish of the surface (as opposed to "accuracy," which describes the dimensional characteristics of the surface). Scratches, pits and chips on the surface, as well as bubbles, flaws and inclusions within the element, are defined by the quality specification. In the range of defect sizes usually permitted for precision optics, these are almost purely "beauty" defects and

have little effect on the function of the system, since the amount of energy they intercept is negligible.

The customary specification for surface defects is a two-number code. The first number originally specified the apparent width of the maximum size scratch in micrometers (it now is the scratch width in tenths of micrometers); the second number is the diameter, in hundredths of a mm, of the maximum size dig or pit. Inspection is by visual comparison with a set of graded standards. Further details of this system are given in MIL-O-13830. A surface quality of 100-60 or 80-50 is adequate for most work. Smaller diameter elements or more critical applications may require a quality of 60-40 or 40-20, which will raise the production cost somewhat. Reticles and critical surfaces may require 20-10 or 10-5 surfaces; such specifications should be called for only when absolutely necessary, because of the greatly increased cost of producing such a "clean" surface.

High-power laser optics may require extremely defect-free surfaces. Dirt, or a pit, may become a damage center and eventually cause the destruction of the optic.

Surface accuracy

Surface "accuracy" deals with the dimensional accuracy of the surface. In the case of a spherical surface, one specifies (1) a "power" tolerance, i.e., how far the mean radius of the surface may depart from the specified value, and (2) a "regularity" tolerance, i.e., how far the surface may depart from true sphericity. The specification is usually in terms of the wavelength of the sodium "D" line, which is 589.3nm. Inspection is an interferometric comparison with a master test plate, by observing the interference fringes (Newton's rings) formed between the surface and the test gauge. The 632.8nm wavelength of the HeNe laser is also frequently specified. The air space between the two surfaces changes one-half wavelength for each fringe.

The effects of the power tolerance, when expressed in fringes (i.e., when the tolerance is small), are usually small. When it is necessary to tolerance the radius, the tolerance should be based on a uniform increment of

surface curvature (reciprocal radius), not radius. This produces radius tolerances that are proportional to the square of the radius. For example, the effect of a radius tolerance of .001" on a one-inch radius is roughly equivalent to the effect of a 10" tolerance on a 100" radius:

$$(C = 1/1 = 1.0 \pm .001 \\ \text{versus } C = 1/100 = .01 \pm .001).$$

The regularity tolerance can be evaluated on the basis of the Rayleigh quarter-wave limit. An irregularity of one fringe introduces an optical path difference of OPD of $(N' - N)/2$ wavelengths, where N and N' are the refractive indices on either side of the surface. For the total OPD to be less than one-quarter wavelength, the sum:

$$\sum_{j=1}^n F_j(N'_j - N_j)$$

(where F_j is the number of fringes of irregularity at the j_{th} surface) must be less than 0.5.

Tolerances of 5 to 10 fringes power variation and $1/2$ to 1 fringe irregularity are quite common. Power tolerances of 1 to 3 fringes with correspondingly improved regularity can be obtained with a corresponding increase in cost. Note that these are shop tolerances with respect to a specific test plate, and that it is advisable to determine what radii are available in the shop as stock tooling before specifying surface "power" in this manner. Frequently the surfaces are not given power tolerances; instead the focal lengths and/or the system performance are toleranced. The changes in radius and curvature corresponding to N fringes over a diameter D for a wavelength are given by

$$\Delta R = 4N\lambda R^2/D^2$$

$$\Delta C = 4N\lambda/D^2$$

Thickness

Surprisingly, thickness tolerances are among the most difficult for a production optical shop to hold. Unfortunately, they are among the more critical tolerances in many systems. Systems in which the ray slope angles are large are usually critical in this regard, meniscus (double Gauss) anastigmats and high-aper-

ture microscope objectives being typical examples.

For ordinary precision work, $\pm 0.1\text{mm}$ is a typical thickness tolerance, although $\pm .15$ or $\pm .20$ is more economical. If extreme care is taken, $\pm .05\text{mm}$ can be held in production, but the cost is high, unless production runs are large enough to justify special tooling, i.e., spot blockers.

Centering

Centering tolerances are twofold. The diameter of an element can readily be held to a tolerance of $+.00, -.03\text{mm}$. The accuracy with which the optical axis is aligned to the mechanical axis (as defined by the element diameter) is usually specified in terms of angular deviation; that is, the deviation of an "axial" ray directed toward the mechanical center of the element. This is convenient, since the total deviation of a system is a (vector) sum of the individual deviations of the elements. On mechanical "cone" centering machines the deviation will be about $1/D$ minutes of arc, where D is the element diameter in inches. Visual centering is capable of much better accuracy, for example, 0.1 minute for long radii. Here the accuracy is a function of the radius and magnification used; 1 or 2 minutes is a typical tolerance.

Note that a decentered element can be considered as a centered element plus a thin deviating wedge. When elements are fabricated without a separate centering operation (for reasons of economy) diameters can be held to $\pm .05$ or $\pm 0.1\text{mm}$ and the wedge (across the diameter) to 0.1 to 0.2mm. The deviation of a thin wedge is $(N - 1) \times \text{Angle}$.

Prisms

Prism linear dimensions, like thicknesses, are difficult to control. One should try to tolerance only dimensions that can be measured; that is, not dimensions to sharp corners that have been beveled off. Tolerances of 0.1 to 0.2mm are typical.

For angles, tolerances of 5 to 10 minutes are typical for normal "precise" work produced on good blocking tools. Tighter tolerances are of course possible, and the roof angles of prisms, for example, are held to seconds by hand correction.

Statistical tolerancing

Consider a stack of disks each 0.1" thick, each made to a tolerance of $\pm .005$, and assume that there is an even chance that the thickness of a disk will fall at any given value within this tolerance. Thus, there is one chance in ten that the thickness of a disk will lie at the small end of the tolerance range, between .095" and .096." When two disks are combined, however, the probability that their total thickness is between .190" and .192" is one-tenth of one-tenth, or one in one hundred.

This gives some insight on the commonly used rule of thumb for tolerancing, which is:

$$T = \sqrt{\sum t^2}$$

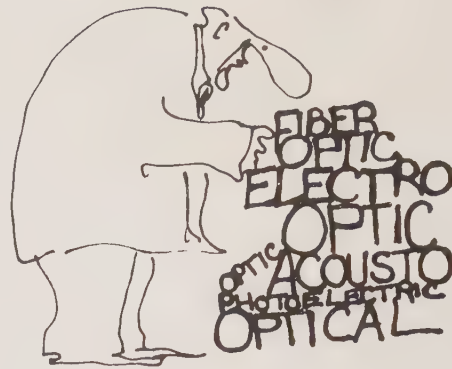
and states that the probable total effect, T , of a set of additive tolerances is equal to the square root of the sum of the squares of the individual tolerance effects. Depending on the distribution of the individual tolerances, 90% to more than 99% of all assemblies will depart from nominal by less than T .

A statistical approach to optical tolerancing is eminently justifiable. Consider a simple air-spaced triplet (Cooke-Taylor) anastigmat. With six curvatures, three thicknesses, two air-spaces and three indices, there are now fewer than fourteen tolerances that additively affect the monochromatic aberrations and focal lengths.

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Positioning Equipment

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Micropositioning Worksheet

Below is a worksheet that can be helpful in evaluating your requirements for selection of micropositioning equipment for a particular application. Klinger Scientific, the source of the worksheet, has found that, though some of the questions can be bypassed in many cases, the form conveniently pulls together what is needed for a full understanding of customer requirements and has aided their staff greatly in properly recommending or designing a micropositioning device.

1. What motions are needed? _____
a. Travel range of each: _____
2. What is being moved? _____
a. Physical size: _____ b. Weight: _____ c. Does load shift, change: _____
d. Does center of gravity change with motion? _____ e. Direction of load: _____
3. What is sequence of the movements? _____
4. What is resolution (smallest needed movement)? _____ 5. Repeatability: _____
6. What is required readability of position? _____
7. What is overall accuracy need for the system? _____
8. Any mechanical or environmental restrictions such as: a. Limited space: _____
b. Explosive atmosphere: _____ c. Corrosive atmosphere: _____ d. Vacuum: _____
e. Extreme Temperatures: _____ f. Radiation: _____ g. High Altitude: _____
EXPLAIN: _____

9. What will our mount sit on? _____
Is flatness a criterion? _____
10. Is perpendicularity between stages critical? _____ To what accuracy? _____
11. Environment, Lab or Production: _____ Number of operations per day: _____

FOR POWER STAGES ADD THE FOLLOWING:

- A. Will microprocessor or computer be utilized? _____ What kind? _____
- B. Is there a speed requirement? _____ How fast? _____/sec.
- C. Does customer require position feedback from stage to guarantee movement? _____
1) Encoder (incremental relative) _____ 2) Analog signal _____
- D. Does the customer need position display? _____ Origin (homing) _____
- E. If using origin for initialization, do they need fixed, absolute position or floating origin (which is lost when power is lost)? _____
- F. Are any movements repetitive in nature? _____

COMMENTS: _____

- G. Order time frame _____
- H. Is project funded? _____

Positioning Equipment: Components and Methods

With required accuracies currently in subwavelength dimensions, and quickly approaching the atomic realm, the design and production of micropositioning devices to meet these demands is largely dependent upon the accuracy of available instrumentation for measurement and control. Devices such as autocollimators, interferometers and quality control test benches, now used extensively, are fast approaching their limits.

Furthermore, tolerances in production of micropositioning components require state-of-the-art machine tools to minimize machining errors in both surface quality and straightness. The lapping and polishing of bearing surfaces often require techniques similar to those employed in production of optical flats. These techniques become extremely difficult to employ when working with the very large parts necessary to construct large-movement micropositioners. The materials used in the micropositioner must be carefully selected for their tensile strength, rigidity, machinability and thermal stability. The construction of large micropositioning devices from steel results in substantial weight but helps minimize the effects of variations in ambient temperature upon the mechanical components of the positioner.

Large positioning systems are often subjected to large loads and forces, and thus the resultant bending, stress and friction affect stability. The wear and tear on a positioner over several hundred hours of operation can result in worn parts, also creating stability errors of a few micrometers that appear as drift of the device's position. Lubricants used to reduce wear and tear often introduce similar effects, primarily from variation in the thickness of the lubricants' film due to contact pressure and to the lubricants' viscosity.

Components of the positioner that have the greatest effect on its accuracy are the mode of measurement, the drive mechanism and the guide system. Positioners that use the drive mechanism as part of the measurement system form a kinematic chain consisting of the motor or drive knob, encoder, drive screw (either lead or ball screw) and nut (see Figure 1). This technique provides the magnitude of rigidity necessary

for precision positioning and leaves only guide precision to control.

The primary function of the guide system is to limit the motion of the device to one degree of freedom, that is, along its axis. One of the most common and successful types of guide system is the ball race (ball-bearing-guided) type (see Figure 2). This system uses a series of preloads to remove side play from the positioner. It should be noted that even the best ball-bearing-guided systems are subject to tracking errors of approximately one micrometer due to change in the equilibrium preloaded state of the device as the positioner moves over its travel. It is advisable that, whenever possible, the load on the positioner be kept as close to the center as possible and lie within the axis defined by the ball-bearing

guides. This will reduce wear and deformation of the ball race.

Current state-of-the-art micropositioners offer a wide selection of varied technologies for methods of actuation. Each of them — piezoelectric, DC servo, stepping-motor or variations on any of these — offers some advantages over the others (see following article).

Though obtaining high resolution (to 10 nanometers) is not difficult, the mechanical design of the positioning device, and the limitations discussed previously, generally result in 0.1 μm linear resolution with approximately $\pm 0.3 \mu\text{m}$ absolute accuracy, and 1 microradian angular resolution with ± 2 microrad absolute angular accuracy.

Gary Spiegel
Klinger Scientific Corp.

USING POSITIONING EQUIPMENT: DEFINITIONS AND METHODS

Determining the number of degrees of freedom for an application or experiment is a two-step procedure. First, one must define the elements being aligned. Having done this, one can then determine the number of adjustments needed to achieve alignment. Before looking into this in greater detail, however, it is helpful to divide all alignment problems into two classes, static and dynamic, and to define these terms.

Static alignment achieves the alignment of an object with refer-

ence to a set of spatial coordinates. Once aligned, the object remains stationary for the duration. In contrast, in dynamic alignment the object undergoes movement during the experiment or application. By definition, dynamic alignment establishes a vector, or path of motion, with reference to a set of spatial coordinates and also achieves specific orientation of the object with reference to the path of motion. Scanning movements all fall into this category.

Seen from another point of view,

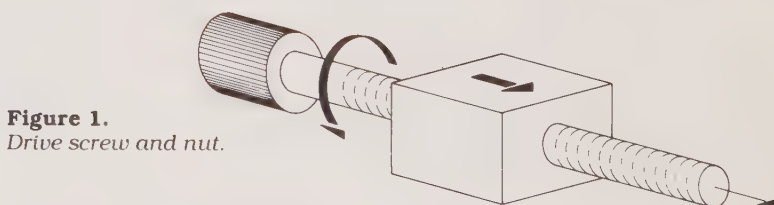


Figure 1.
Drive screw and nut.

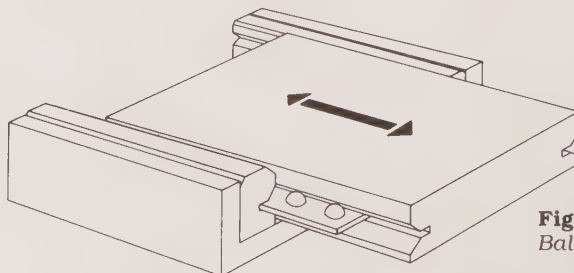
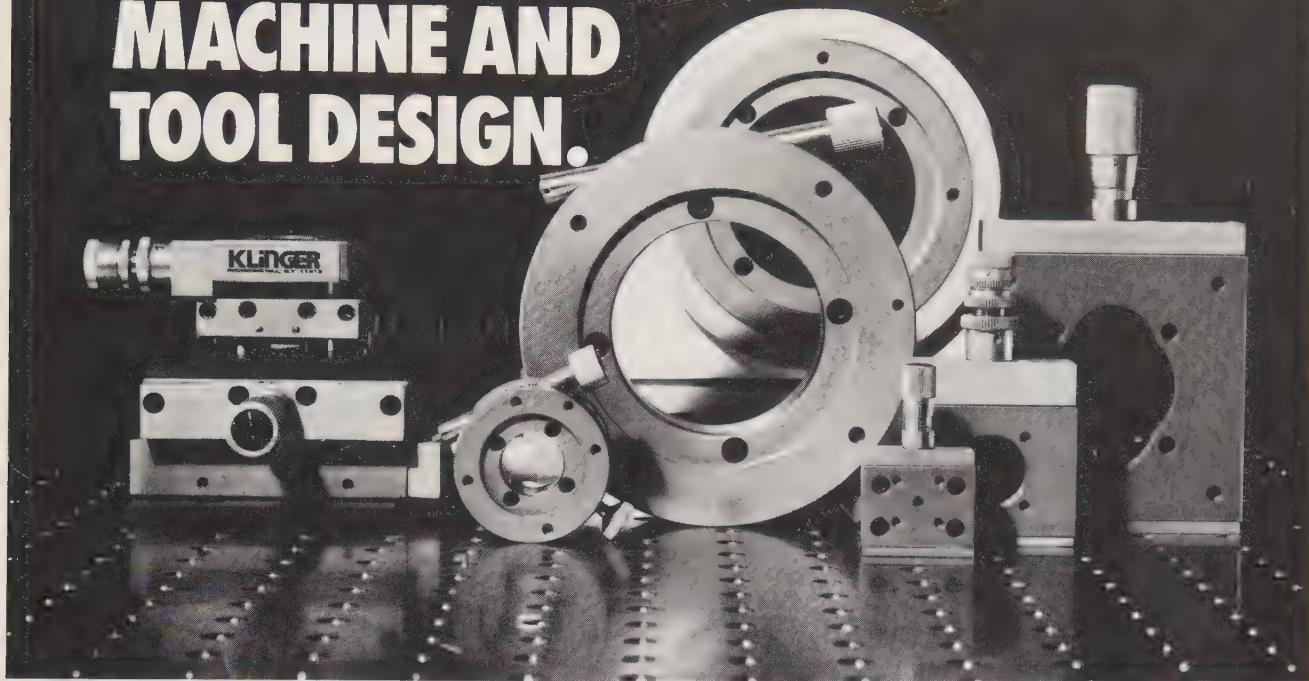


Figure 2.
Ball race guide system.

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such dynamic alignment involves two objects: the system element, which must be oriented with reference to a scanning device, and the scanning device itself, which must be oriented to, say, an optical axis. Obviously, problems involving scanning movements must be treated differently from those involving static alignment.

In static alignment, the maximum number of degrees of freedom is six: three in orthogonal translation and three in orthogonal rotation. In dynamic alignment, six degrees of freedom may be required in orienting the object relative to the mechanical axis of the scanning device. Additional degrees of freedom — as many as five — may be required in aligning the scanning axis to the system coordinates. In practice, very few alignments require all eleven degrees of freedom. To insure that no necessary adjustments are overlooked, start with the maximum and eliminate those that are not required.

Range vs. resolution

Range and resolution must be considered together, inasmuch as these parameters are determined by the mechanical advantage of the adjusting mechanism — the greater the mechanical advantage, the higher the resolution. Since the limitation in range is determined by the limit of travel of the driving member, usually a screw or micrometer, one can say that the greater the mechanical advantage, the lower the range.

In rotary devices with unlimited actuator travel, the relationship between range and resolution is somewhat different. In such devices, the higher the resolution, the greater the motion of the actuator. This consideration must be carefully weighed in situations requiring frequent traversing of large angles.

In considering a tradeoff between range and resolution, greater weight should be given to resolution. Since the required range can be predicted with greater certitude, only a nominal safety factor need be added. In contrast, the requirement for resolution is more difficult to predict, so that a higher safety factor is advisable here. And while higher-resolution capability can enhance functioning of the positioner, no useful purpose would be served by surplus capability.

Resolution vs. repeatability

Mistakes in specifying positioning equipment frequently result from confusing the terms "resolution" and "repeatability." Resolution may

be defined as the minimum adjustment increment effectively achievable by the mechanism. In addition to mechanical advantage, other resolution-limiting factors are the actuator stiction (static friction), friction in the mechanism, and backlash. Repeatability is usually defined as the limit to which a predetermined setting can be duplicated by observation of the optical phenomena. Thus repeatability becomes in effect another limitation on resolution.

Cross-coupling

Cross-coupling is a byproduct of imperfect geometry in the alignment system. It becomes a serious problem whenever the need for alignment is critical, especially in situations involving multiple degrees of freedom.

Cross-coupling is totally absent from alignment systems in which the axes are perfectly orthogonal and coplanar, and in which the components are in perfect alignment with the positioner's coordinates. Since this condition is never achieved in practice, it is well to define a tolerable level of cross-coupling.

The degree to which cross-coupling can be tolerated depends on the complexity of the alignment process. In simple problems, such as aligning a laser beam with a reference axis, cross-coupling may have no worse effect than requiring additional effort to achieve alignment. In other problems, especially those in which alignment can be successfully carried out only by varying one degree of freedom at a time, cross-coupling can frustrate the alignment process seriously.

Types of cross-coupling

Cross-coupling occurs whenever (a) the alignment axes of the positioner are nonorthogonal; (b) the alignment axes are not coincident with those of the positioner; and (c) the translator slide departs from linearity.

Figure 3 illustrates the type of cross-coupling resulting from nonorthogonality. Movement along the adjustment axis X-X produces displacement ΔY in the Y-Y axis. This type of cross-coupling can easily be offset with corrective movement in the Y-Y axis. Similar effects are produced with rotation about two non-orthogonal axes.

When the component axes do not coincide with the positioner axes, translation cross-coupling results. This can be corrected only by the elimination of the offset e in Figure 4. If this is not feasible, it may be neces-

sary to add offsetting translational adjustments. In some instances, the design of the mount may permit placement of the component near the desired location, but the alignment is so critical that manufacturing tolerances are insufficient to insure the desired alignment. In such applications, there is no recourse but the incorporation of additional adjustments to improve preciseness.

The cross-coupling produced by a positioner with orthogonal but nonplanar axes is similar to that described above. If the displacement between the axes is small, cross-coupling can be minimized by placing the component midway between the axes.

The cross-coupling produced in translators with nonlinear tracks or bearings has linear as well as rotational components. Both of these are usually small, so that corrective adjustments need be considered only in the most critical applications.

Backlash

In the ideal micropositioner, the movements of the driving element and the driven elements are linked in a fixed relationship, i.e., every movement of the driven element is a function of a related movement in the driving element. Departures from this relationship are known as "backlash," "shake" and "play."

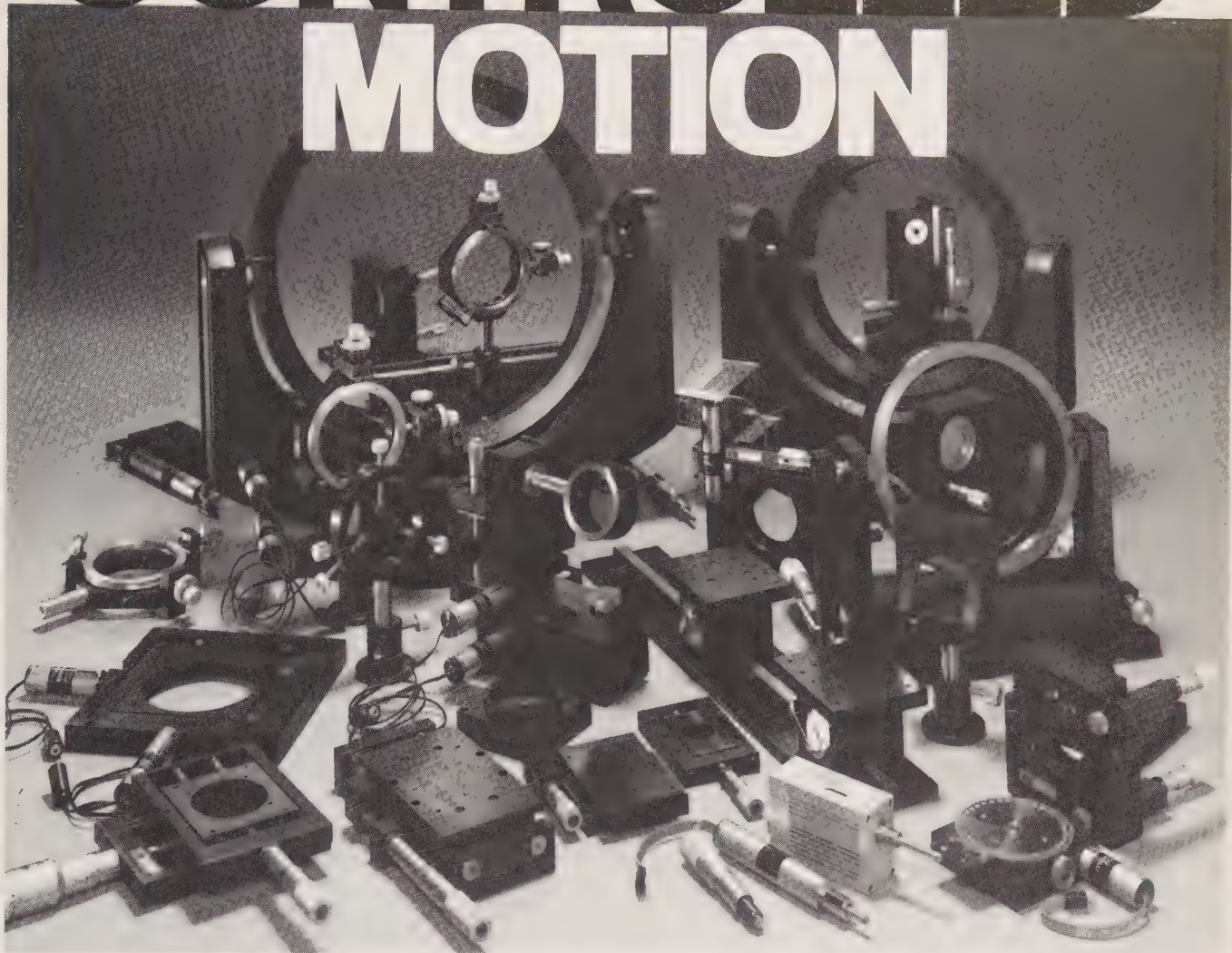
The latter terms refer to uncontrolled movement induced in the moving platform because of bearing looseness. The only corrective actions that will eliminate these unwanted movements are either adjusting the fit or spring-loading the platform.

The term "backlash" refers to the lost motion between the driving and the driven elements and is observed whenever the driving element is reversed. The amount of backlash is a function of the type of coupling between the driving and driven member. Devices that rely on a precision fit between members in the drive train are subject to some residual backlash. The most reliable method of eliminating backlash is the use of spring-loading, which insures contact between the driving and driven members regardless of the direction of drive. But spring-loading lowers resolution, because of the added friction in the adjustment elements.

Motion and drive mechanisms

Many methods are available to produce the motion or combination of motions required for a particular application while constraining the other degrees of freedom. We will

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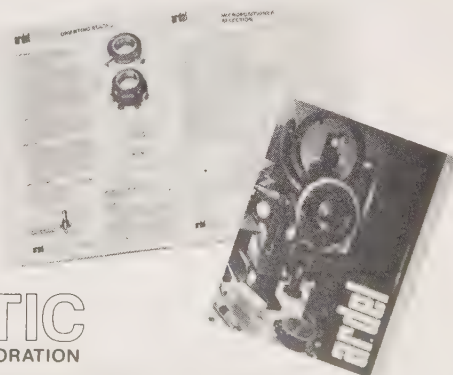
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Figure 3.
Cross-coupling caused
by nonorthogonality.

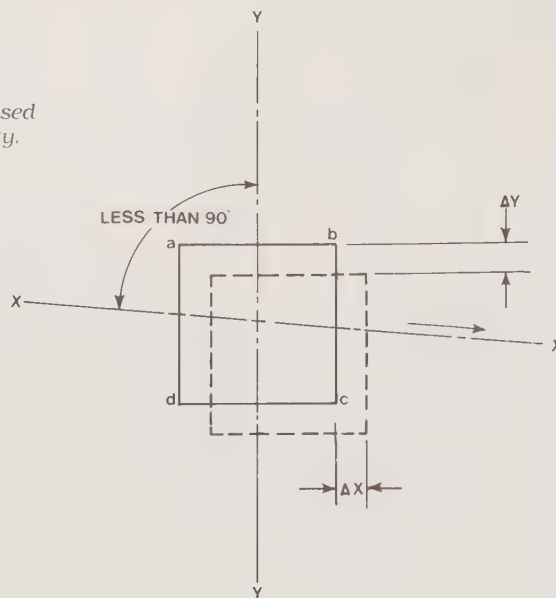
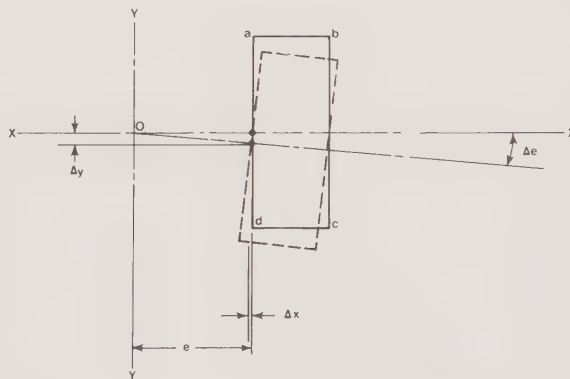


Figure 4.
Translation cross-coupling.



cover the most common general-purpose equipment available and used in the fiber optic, laser and electro-optical fields, considering linear and rotary motions separately, following that with the drive mechanisms that move these devices, and concluding with a brief discussion of how modularity and stackability affect performance.

● **Linear motion:** The common name for a basic linear positioner is a translation stage. These devices usually contain either dovetails, ball-bearings, crossed roller bearing or air bearings; almost every manufacturer of positioning equipment for general purposes in the fiber optic, laser and electro-optic market employs at least one of these.

Dovetail slides are probably the least expensive method of producing linear motion. The dovetail consists of two sets of interlocking angles to constrain the rotary and other linear motion while allowing movement along the axis of the angle. The con-

tact lines or planes on the angle surfaces usually have a low stiction pad or coating to minimize friction. By carefully specifying machining tolerances on the angles, and matching bearing materials for low stiction, a stable linear slide mechanism can be produced.

Typical unwanted motion in dovetail slides includes skipping or jumping when attempting fine positioning. Dovetails are best used for infrequent movement along an axis, with a reasonable degree of accuracy, followed by locking in place. A common combination is a dovetail optical bench or rail in conjunction with one of the following methods.

Ball bearings are probably the most widely used device to produce linear motion. Precision ground and hardened rods are captured to form a vee channel in which a hardened ball rides. Opposing sets of ways and multiple balls provide the necessary additional constraints on the other degrees of freedom, and the point-line contact of the rolling balls pro-

duces low friction for ease of movement. This type of contact also responds well to loading to remove play without, up to a point, seriously increasing friction. The quality of the balls' sphericity and concentricity as well as the surface quality and hardness of both balls and rods determines the overall performance of the slide. Inexpensive ball and way components of high quality are widely available.

But the additional precision of the ball-bearing slide is not without cost. Assembly of the balls and ways requires time and a reasonable level of skill to fully utilize the advantages of this technique. To build a typical ball-bearing stage with one inch of travel requires at least a half-hour of time, and the manual dexterity to insert small balls into a ball cage (to keep the balls evenly spaced and to prevent them from falling out) one at a time. Then, to optimize performance, the bearing must be loaded to eliminate play. Depending on the length of the bearing, many adjustments in loading may be required to remove play from the entire length.

Cross roller bearings are similar to ball bearings: Rather than a rolling ball, a rolling cylinder, retained in a seat, provides a low-friction line contact. The cylinder provides a larger contact surface to support greater loads without increasing friction. The pros and cons of the cross roller are very close to those of the ball bearing. The major benefit is its large load capacity as against a comparable ball slide. But this type of bearing, because of the manner in which the crossed roller is produced, costs slightly more than ball-bearing assemblies. If additional load capacity in a limited space envelope is required, then the additional cost over and above that of the ball-bearing slide assembly may be warranted.

Air bearings are the latest development to find application in fiber optic, laser and electro-optic positioning. As the name implies, the bearing is an air support. In its basic form, air is forced from a central column into a sealed cavity. This force "floats" the opposing surface. By forcing air against all surfaces, except those in the direction of travel, in an extremely precisely controlled manner, unwanted motions are eliminated. One of the great advantages of this is that it is essentially frictionless. The great care and expense required in the machining (and perhaps lapping) of the surface against which the air is forced, as well as the critical layout of the air ports, are among the factors the user of the air bearing must confront.

Using Positioning Equipment

Along with the cost, the size and the requirement for continuous air pressure constitute the major stumbling blocks for the air bearing system. Typical cost for an air-bearing slide is up to ten times that of conventional bearing slides of similar size differentials for comparable travel. Air bearings make sense for ultraprecise positioning, although at these levels of precision one must be careful that the drive mechanism is as accurate as needed. They have excellent wear characteristics for continuous or repetitious movement because of the lack of contact bearing surfaces.

The decision to use an air bearing must weigh the high cost against performance. Given this tradeoff, the air bearing is not a frequent choice for the standard experimental setup.

● **Rotary motion:** The choices for producing rotary motion, devices commonly called rotators, are more limited. There are essentially only two techniques, ball bearings or air bearings.

For ball-bearing rotators the bearing race is the crucial element. In most rotators this is a seat or vee groove machined in a ring of hardened ball rides. A second matching ring and groove sits on top of the balls to provide a rotating surface. To allow this bearing to work in planes other than the horizontal, it must also be loaded. Such loading must be sufficient to handle specified loads when mounted in other planes, yet not so much as to brinell the groove or constrain the rotation.

Rotary air bearings, like linear air bearings, are air-support devices with essentially the same advantages and drawbacks. Again the high-precision, frictionless, no-wear characteristics must be balanced against the cost, and the capability of the drive mechanism to utilize these qualities fully considered.

One specialized version of the rotator is the optical mount. Typically, the mount is a limited-range, two-axis rotator that uses some form of tangent-arm drive technique. The important features here are not so much related to the performance of the bearing, although most mounts are the ball-bearing type and of high quality, but to the location of the component in relation to the axis of movement, the amount of cross-coupling between the axes, and the resolution obtainable from the drive mechanism. Guaranteeing the component rotates at the intersection of the axes of motion insures that only rotation of the component occurs, without introducing linear motion

that can compound the difficulty of critical alignments.

True gimbal mounts, with independent rotational motion and the rotational axis correctly oriented to the component, eliminate another form of cross-coupling or crosstalk that can be equally frustrating — movement of both rotational motions when only one is desired. The final concern is resolution. Here again it is important that the performance of the bearing, the amount of cross-coupling and the resolution of the drive be closely matched to obtain a mount that is useful for general applications.

Drive mechanisms

We have addressed the problems of the components that move. Now we must complement this with a discussion of the relationship between these moving elements and the devices that move them. We will discuss aspects of both manual and motorized drive mechanisms.

Manual drive mechanisms are primarily designed to provide human hands with a mechanical advantage for fine positioning, and sometimes to track or measure position. Lead screws are one of the most common drive devices. Fine-pitch high-quality screws at reasonable cost are readily available for positioning that doesn't require readout of information. But probably the most common drive device is the micrometer head: It has well-documented accuracy at reasonable cost with standard markings to track or measure position.

A variation on both of these is the differential screw or differential micrometer. The only difference between the two is that the micrometer has scale markings to read out position. The differential screw is a screw within a screw or linear reduction gear, which is usually two screws of different pitch mounted so the movement of the coarser pitch produces a reduced movement in the internal finer-pitch screw. But the differential screw has only a limited range of motion.

Making a choice

The choice between lead screws, micrometer heads or differential screws for a drive device is fairly straightforward. Provided that position measurement is not necessary, a coarse-pitch lead screw offers a good tradeoff of resolution for rapid adjustment. For finer positioning, the micrometer head is a solid choice even if measurement is not a consideration. Yet the cost for the markings is marginal and they can prove use-

Positioning Equipment

ful at a later date. Typical range for an accurate lead screw or micrometer is a maximum of about 2 inches. But accuracy is difficult to maintain when a single lead screw's travel is longer. Therefore, a dual drive with opposing screws or micrometers is often employed.

The range-vs.-resolution tradeoff should also be examined to determine if the high resolution is necessary over the entire range of motion. The differential screw or micrometer offers the best resolution of all the manual drives, but its severely limited range must be taken into account, so that sufficient travel is available for the application.

One other drive mechanism commonly found in rotators is a worm wheel and gear drive: A gear, integral with the rotator bearing race, is driven by a worm wheel. Selection of gear reduction can achieve high resolution, but backlash can become severe if the gear is eccentric.

Motorized micro drives

Motorized drive techniques can be employed on such stages. An examination of a few of them can help insure selecting the right drive.

Motorized micropositioning for general research applications has several advantages over manually adjustable devices, as follows:

1. High spatial resolution;
2. Computer control;
3. Positioning in hostile environments;
4. Elimination of the mechanical disturbance caused by manual operation;
5. Simultaneous multiple movements;
6. Continuous smooth motion over large areas;
7. Time dependent movement — slow or fast scanning for a given time period; and
8. Remote positioning.

There are several features that are desirable and perhaps necessary to make a motorized positioner useful for most purposes. In a general research environment they include:

- Small size for use in limited areas;
- Vacuum compatibility;
- Up to 2 inches of travel;
- Uncomplicated control;
- Position readout; and
- High accuracy/repeatability.

Three common techniques developed to satisfy these advantages and requirements are DC motors, stepping motors and piezoelectric crystal (transducer) drives. Each method has qualities that, for a given

application, make it the most desirable selection.

● **DC Motors:** DC motors are the most cost-effective method for motorized positioning. There are many small, high-quality, inexpensive DC motors available that have optional reduction gearheads. By coupling the motor and gear reduction with some system of converting the gear-train output shaft rotation into linear movement — a lead screw, for example — linear position control is possible. As with all types of motorized drives, the technique employed to control the motor plays a role almost as crucial as the actual mechanical device.

Most DC motors used in micropositioning applications require between 5 and 25VDC. This low voltage requirement enhances the cost-effectiveness of these drives. Very simple power supplies, or even battery sources, may be used. Control of the motor speed and direction can be accomplished simply by varying the voltage to change speed and changing the polarity to change direction. Variable potentiometers effectively provide this speed control.

Drawbacks to simple DC motors include slow maximum speed, usually a result of the gear reduction system needed to achieve high resolution, low load capacity at top speed, and no indication or readout of position. Of these, the lack of position readout is the most critical. The simple DC motor is most effective in applications where an external source provides position feedback. The source of this might be direct observation, a CCTV system, a microscope, or a linear variable differentiation transformer or some other type of linear encoder.

A major improvement on the simple DC motor drive is an optical encoder, because it can provide position feedback. It usually consists of a shutter or wheel device attached to the motor. As the motor's drive shaft rotates, turning the shutter or wheel, it interrupts a light beam between an LED and detector. This detector in turn sends out a number of electrical pulses for a given rotation of the motor shaft. With the correct gear reduction and lead screw, pulses correspond to small linear movements. (See "Optical Encoders," page 21.)

The optically encoded DC motor can provide the same smooth vibration-free positioning as the simple DC motor, and the pulses from the encoder can keep track of position. Depending on the type of encoder, you can also maintain high resolution and small size, and, since feed-

back of position is the key to computer control, the encoder provides a means of computer communication.

The drawbacks to the optically encoded DC motor include those for the simple DC motor. The encoder usually adds one compounding factor to operation, and that is backlash. But backlash can be electronically compensated for, so that the actual effects on position indication are minimal.

● **Stepping Motors:** Stepping motors provide exactly what their name indicates: By energizing the motor coils in a designated sequence, the stepping motor rotates a fraction of a 360° turn. This is usually expressed in a number that divides into 360° evenly, such as 1.8°, 7.5° or 15°. It can also be expressed as the number of individual fractional shaft rotations or steps per one motor revolution, such as 200 steps/rev, 48 steps/rev or 24 steps/rev.

Two types of stepping motors most frequently encountered are the variable reluctance (VR) and permanent magnet (PM). Our discussion will concern itself with the VR stepping motors, although the characteristics of the PM type are essentially the same. VR steppers typically require between 12 and 30VDC to energize the appropriate motor coils or phase in a given sequence. The frequency of the sequence produces the speed at which the motor shaft rotates.

Control of the motor shaft rotation, or shaft steps, can be accomplished with digital electronics. Unlike the DC motor, which operates by varying a voltage, the stepping motor takes a single discrete step for each sequence of drive voltage it receives, a sequence that can be programmed using integrated circuits. The ICs establish a timing frequency for drive transistors that actually send the operating pulse sequence to the motor. The stepping motor's capacity to operate using digital electronics enhances its use as a drive source for micropositioning.

Disadvantages of the stepping motor start with the method of keeping track of position. Counting pulses to the stepping motor as a means of indicating position leaves room for error. If the motor is overloaded or stalls, drive pulses can still be sent to the motor indicating movement, yet no motion is taking place.

● **Piezoelectric transducers:** Piezoelectric translators are another approach to motorized micropositioning. In most micropositioning applications the desired result is a linear motion. With DC and stepping

motors it is necessary to convert the motor shaft rotation into linear movement with mechanical reduction components, which limits the final accuracy of the motor.

Piezoelectric translators operate inversely to the piezo effect, which occurs when mechanical pressure, applied to certain polarized crystals, causes the crystals to generate an electrical field. By reversing this process on appropriate materials, usually artificially polarized ceramic stacks, a mechanical movement can be produced by applying electrical energy: Varying the voltage produces a varying mechanical movement. Using this technique, it is possible to produce movements as fine as 0.001μm.

This extremely fine resolution is the greatest advantage of the piezoelectric "motor." When you couple extremely fine resolution with the lack of mechanical components that are required on other motors to produce linear motion, the repeatability and accuracy of the piezoelectric crystal drive is quite good.

The greatest disadvantage for general micropositioning applications is the limited range of motion that piezoelectric drives can produce. Forty micrometers is about the maximum travel that can be obtained from a ceramic stack. It is also important to note that the manufacturing of these devices is a complicated procedure and as a result makes them the most expensive of motorized drives.

Combining motions

To complete our picture of the component approach to positioning instrumentation, we examine how combinations of motions can be achieved and what problems can result.

For the purpose discussed here, adjustment combinations must be achieved by coupling one orientation device to another. The order in which they are stacked will affect the alignment process.

In general, it is preferable to begin a stack with all of the translational devices supporting all of the rotational devices, since the former in effect establish a set of orthogonal coordinates. By retaining the translation device at the bottom of the stack, the established linear coordinates maintain their fixed orientation. If the reverse were attempted, every angular adjustment would result in an angular displacement of the linear coordinate, thereby complicating alignment.

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PHOTOMETRIC TERMINOLOGY

Luminous Flux (Φ_V)

*Lumen

Illuminance (E_V), $E_V = \Phi_V/A_P$ Lumen/cm² = phot*Lumen/m² = luxLumen/ft² = foot candleLuminous Intensity (I_V), $I_V = \Phi_V/\Omega$

*Lumen/steradian = candela

Luminous Emittance (M_V), $M_V = \Phi_V/A_S$ Lumen/cm²*Lumen/m²Luminance (L_V), $L_V = \Phi_V/\Omega A_S$
(Brightness)*Lumen/m² - steradianLambert = $\frac{1}{\pi} \frac{\text{candela}}{\text{cm}^2}$ Foot Lambert = $\frac{1}{\pi} \frac{\text{candela}}{\text{ft}^2}$

RADIOMETRIC TERMINOLOGY

Radiant Flux (Φ_E)

*Watt

Irradiance (E_E), $E_E = \Phi_E/A_P$ Watt/cm²*Watt/m²Radiant Intensity (I_E), $I_E = \Phi_E/\Omega$

*Watt/steradian

Radiant Emittance

(M_E), $M_E = \Phi_E/A_S$ Watt/cm²*Watt/m²Radiance (L_E), $L_E = \Phi_E/\Omega A_S$ *Watt/m² - steradianDefinitions:† A_S = area of the emitting source A_P = area of the receiving photodetector Ω = measurement solid angle

*Signifies International System (SI) units

†For radiant definitions, substitute the word radiant for luminous

TERMS DEFINED

- (1) Luminous Flux: total luminous power emitted from a source and expressed as lumens.
- (2) Illuminance: flux density at a given distance from the center of a source. It is equal to the total flux divided by the received surface area over which it is spread.
- (3) Luminous Intensity: ratio of luminous flux emitted by a source to the solid angle of emittance of that source.
- (4) Luminous Emittance: ratio of the luminous flux emitted to the area of the source.
- (5) Luminance: ratio of luminous intensity to the area of the source projected in the direction of view.

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Radiometry and Photometry:

Applications

Optical radiation is commonly taken to cover the wavelength range from $0.2\mu\text{m}$ (or 200nm) in the UV to $10.6\mu\text{m}$ (or 10,600nm) in the infrared. Such arbitrary limits are set on the short-wavelength end by atmospheric absorption, and on the long-wavelength end by substitution of the word "heat" for "light." Almost no one is interested in measuring light over this entire range, so most instrumentation is designed to cover a portion of it. In addition, each application generally has its own signal level range as well as its own wavelength range.

Radiometers and photometers

Most general light measurements fall into this category. A typical radiometer has a silicon detector, cosine spatial response input optics and digital readout unit with a six or seven-decade dynamic range. Such a system can measure irradiance levels as low as $10^{-9}\text{W}/\text{cm}^2$ (for a comparison, daylight can produce about $10^{-1}\text{W}/\text{cm}^2$). A system employing a photomultiplier can make measurements as far down as the 10^{-12} range. The spectral range of a silicon detector is typically 300nm to 1100nm, though use of UV-enhanced silicon can take that down to 200nm. Some systems use vacuum photodiodes for measurements in shorter wavelength ranges.

As for photometers, a wide variety is available for research, with six and seven-decade dynamic ranges, reading down to 10^{-3} footcandle (sunlight gives about 10,000 footcandles at the earth's surface). For these devices detector-filter combinations typically match the visual spectral sensitivity — $V(\lambda)$ — to within an integrated error of 3-4 percent, which is adequate for "white" light sources.

Colored sources, on the other hand, such as red and green airplane running lights, can produce significant errors with a normal photometer. But calibration of a photometer for the specific colored source to be measured can minimize this shortcoming. Furthermore, the measurement of total lamp output in units of mean spherical candlepower can be accomplished with the addition of a calibrated integrating sphere.

Another specialized application, that of effective intensity measurement of flashing lights, can be made directly with a time-integrating pho-

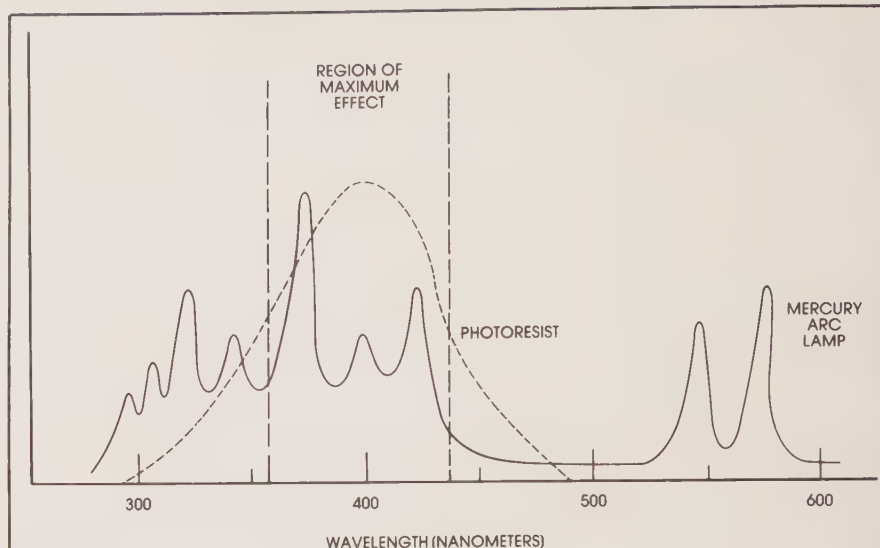


Figure 1.

Spectral energy distribution curve of a mercury arc lamp vs. spectral sensitivity curve of a photoresist monomer.

tometer. For low-light-level applications the required scotopic visual response — $V'(\lambda)$ — is generally available as an optional extra with some photometers. Recent developments include instruments that directly measure chromaticity coordinates and that provide low-cost luminance measurements with coaxial optics.

Laser power and energy meters

Laser power meters are basically of two types, those with thermal detectors and those with silicon detectors. The thermal detectors have the advantage of flat spectral response over a broad spectral range, but because of their low sensitivity they are more difficult to use than silicon detectors. Meters are available that measure from 10^{-9} to 10^{+2}W (using attenuation). For laser energy measurement there are integrating radiometers with response times in the low nano-second range. These high speeds, however, aggravate a common problem: detector current saturation caused by very high peak pulse power at low energy levels. One laser radiometer provides a warning light.

Fiber optic radiometers

This new and highly specialized field differs from more traditional areas in both wavelength range and measurement units. Spectrally, such radiometers concentrate on the range from 800 to 900nm with a silicon detector and 1300 to 1600nm with a

germanium detector. The unit of fiber optic transmission measurement is the decibel, defined as: $\text{dB} = 10 \times \log(\text{power out}/\text{power in})$. Typical radiometers measure up to 80dB loss from a one-milliwatt or one-microwatt input signal. Another measurement instrument, the optical time domain reflectometer, serves the purpose of locating fiber optic cable defects by measuring the return time of a short-duration light pulse (see "Fiber Optic Test and Measurement").

Spectroradiometers

Spectroradiometer systems vary in complexity, from simple systems where the spectral scanning, data recording and data reduction are all manipulated by hand, to those systems that are fully automated for all functions, including data processing to provide integrals and weightings of the spectral data over a designated band such as UVA irradiance, illuminance and color coordinates. A silicon-based system can read down to $10^{-9}\text{W}/\text{cm}^2\text{-nanometer}$ from 400nm to 1000nm; a photomultiplier can increase the sensitivity by 10,000 but over a smaller wavelength range. Scattered light rejection approaches 1000:1 for a single monochromator, and 1,000,000:1 for a double monochromator. Such low-scatter systems are used for UV spectral measurements of light sources with large amounts of near-UV and visible irradiance. Both the sun and tungsten

sources fall into this category. But this technique does not work for the deep UV — less than 300nm — spectral measurements of sunlight because solar spectral irradiance levels change by a factor of ten million from 280nm to 320nm.

Solar power and energy

This is a growing field for a number of reasons. Most obvious, spectral analysis of the sun is important in the development of solar cell detectors, especially of the silicon variety, because careful matching of the spectral sensitivity of the detector with that of sunlight, even on cloudy days, increases the efficiency of the device. But though the use of a spectroradiometer for this purpose is by far the most accurate measure of sunlight's energy content, it is somewhat expensive and time-consuming.

A less accurate but faster indication can be obtained by the use of a broadband cosine-response-corrected detector. By cosine response we are referring to the fact that energy reaching the earth's surface varies as the cosine of the incident angle. The cosine response of the detector should be capable of operation over the full spectral range of the detector.

Many detectors are also available in underwater versions as well. The value of such measuring devices may not be readily apparent, but for example in the new class of solar collectors for water heating, it is valuable to know the level of irradiance within a liquid. This can give the heat engineer some idea of the heat transfer/absorption characteristics of other liquids. Another application is in the new field of underwater high-nutrient plant harvesting and cultivation. For many years sea kelp has been harvested off the coast of Nova Scotia — a valuable source of protein and iodine, just as are some types of seaweed. Study is now going on of artificial lighting methods to enhance the growth rate of kelp under artificial conditions.

A standard radiometer with a silicon detector has a spectral sensitivity range of 300-1100nm, including about 75 percent of the sun's output. A thermal detector with a quartz window is sensitive from 250nm to 3 μ m, covering 97 percent of the sun's output. But thermal detectors have disadvantages: They are more expensive than silicon, have less dynamic range, and are more temperature-sensitive.

Medical applications

Light measurement requirements in medicine fall into two areas: irradiance measurements in phototherapy and laser power measure-

ments in surgical applications. Ultraviolet light in the UVA (320-400nm) and UVB (280-320nm) ranges is used in the phototherapy of psoriasis. Longer wavelengths (420-480nm) are used in the treatment of hyperbilirubinaemia. The radiometers used are usually low-cost dedicated instruments, since the wavelength range and dynamic range (0.5-20 milliwatts per square centimeter) are fixed. The power and versatility of a research radiometer are not needed; in fact, the complexity of such an instrument can cause problems for non-technical operators. The detector's spatial response in this application must be very close to perfect cosine response; moderate deviations can cause 30 to 40 percent measurement errors.

Laser applications generally involve power measurements of focused beams. The power and energy meters discussed above are used for these measurements.

Photochemical etching

Now highly accepted as a pattern formation technique in the manufacture of semiconductor devices, printed circuits, color television tubes and small metal parts, photochemical etching is under constant pressure for process refinement. Thus it is essential to understand and control all parameters affecting the process, including the energy supplied to catalyze and complete the reaction. The photochemical etching process generally consists of a photo-sensitive monomer that polymerizes into an etchant-resistant coating when photochemical energy from a UV source impinges upon it. These monomers, familiar to most as photoresists, are sensitive to a fairly narrow band of the spectrum ranging approximately from 300-500nm.

Defining energy as the sum of instantaneous power added over time, the energy supplied to the photochemical etching process can be assessed as the amount of instantaneous power irradiating the monomer over the spectral range specified above, as added up over the time exposure. But Figure 1, which shows the relative spectral energy distribution curve of a mercury arc lamp superimposed upon the relative spectral sensitivity curve of a photoresistive monomer, illustrates that the maximum effect of radiation is in the wavelength between 350-450nm and that little or no effect is produced by wavelengths outside this range. Because the total energy absorbed by the process of photochemical etching during the length of exposure is

crucial to the process, radiometric and photometric instruments designed specifically for light that causes such reactions are of great value in optimizing exposure.

UV polymeric curing

In a similar vein, within the past few years there has been considerable development and practical application of UV-induced crosslinking. Older methods of curing often involved large gas or electric heating ovens, consuming as much as 50,000W of energy or more per hour. UV curing typically consumes less than 5 to 10 percent of this amount. Another benefit of UV curing is the almost total elimination of polluting byproducts.

Materials that contain photocurable monomers are generally cured in the UV portion of the spectrum from 240nm to 400nm. The important additive in these materials is the photoinitiator — sometimes called the absorbing dye — that absorbs the UV irradiance and produces the polymerization. Four methods produce polymerization:

- Creation of an ion-charge-exchange-excited condition that goes to a radical induced polymerization;
- The efficient system whereby participation (fragmentation) yields radical species that induce direct polymerization;
- Hydrogen abstraction by an electronic excited molecule, which opens up a radical location that then can induce polymerization;
- The energy transfer from the electronically excited molecule to a new reactive double bond system.

Several manufacturers have medium and high-pressure mercury arc lamps that produce UV energy levels that are extremely efficient in UV curing. But the irradiance level reaching the curable material is critical: If the threshold value for polymerization is not obtained, curing will not take place.

This is where the UV curing radiometer comes in. Measurement of the UV irradiance on a product or sample in a characteristic geometry — for instance, an installation of the conveyor type with linear arc lamps — together with such factors as the belt speed, the choice between an elliptical reflector or a paraboloidal reflector, and advantages of highly focused slit irradiance enable an engineer to predict and control quality and production-line efficiency.

Jack Kelley
International Light Inc.
Charles P. Comeau
GCA Inc.

Blackbody Radiation Functions

λT , cm°deg	$\frac{W(\lambda, T)}{W_{\max}(T)}$	$\frac{\int_0^\lambda W d\lambda}{\int_0^\infty W d\lambda}$	λT , cm°deg	$\frac{W(\lambda, T)}{W_{\max}(T)}$	$\frac{\int_0^\lambda W d\lambda}{\int_0^\infty W d\lambda}$	λT , cm°deg	$\frac{W(\lambda, T)}{W_{\max}(T)}$	$\frac{\int_0^\lambda W d\lambda}{\int_0^\infty W d\lambda}$
0.050	2.999 X 10 ⁻⁷	1.316 X 10 ⁻⁹	0.091	6.373 X 10 ⁻³	1.013 X 10 ⁻⁴	0.44	6.961 X 10 ⁻¹	5.492 X 10 ⁻¹
0.051	4.775 X 10 ⁻⁷	2.184 X 10 ⁻⁹	0.092	7.165 X 10 ⁻³	1.166 X 10 ⁻⁴	0.46	6.464 X 10 ⁻¹	5.796 X 10 ⁻¹
0.052	7.452 X 10 ⁻⁷	3.552 X 10 ⁻⁹	0.093	8.030 X 10 ⁻³	1.339 X 10 ⁻⁴	0.48	5.990 X 10 ⁻¹	6.079 X 10 ⁻¹
0.053	1.142 X 10 ⁻⁶	5.665 X 10 ⁻⁹	0.094	8.973 X 10 ⁻³	1.532 X 10 ⁻⁴	0.50	5.543 X 10 ⁻¹	6.341 X 10 ⁻¹
0.054	1.718 X 10 ⁻⁶	8.871 X 10 ⁻⁹	0.095	9.998 X 10 ⁻³	1.747 X 10 ⁻⁴	0.52	5.125 X 10 ⁻¹	6.583 X 10 ⁻¹
0.055	2.545 X 10 ⁻⁶	1.366 X 10 ⁻⁸	0.096	1.111 X 10 ⁻²	1.986 X 10 ⁻⁴	0.54	4.735 X 10 ⁻¹	6.807 X 10 ⁻¹
0.056	3.709 X 10 ⁻⁶	2.068 X 10 ⁻⁸	0.097	1.231 X 10 ⁻²	2.252 X 10 ⁻⁴	0.56	4.375 X 10 ⁻¹	7.013 X 10 ⁻¹
0.057	5.326 X 10 ⁻⁶	3.084 X 10 ⁻⁸	0.098	1.360 X 10 ⁻²	2.546 X 10 ⁻⁴	0.58	4.042 X 10 ⁻¹	7.204 X 10 ⁻¹
0.058	7.544 X 10 ⁻⁶	4.532 X 10 ⁻⁸	0.099	1.500 X 10 ⁻²	2.870 X 10 ⁻⁴	0.60	3.735 X 10 ⁻¹	7.381 X 10 ⁻¹
0.059	1.054 X 10 ⁻⁵	6.568 X 10 ⁻⁸	0.100	1.649 X 10 ⁻²	3.228 X 10 ⁻⁴	0.62	3.453 X 10 ⁻¹	7.544 X 10 ⁻¹
0.060	1.455 X 10 ⁻⁵	9.395 X 10 ⁻⁸	0.105	2.563 X 10 ⁻²	5.591 X 10 ⁻⁴	0.64	3.193 X 10 ⁻¹	7.694 X 10 ⁻¹
0.061	1.985 X 10 ⁻⁵	1.327 X 10 ⁻⁷	0.110	3.785 X 10 ⁻²	9.162 X 10 ⁻⁴	0.66	2.956 X 10 ⁻¹	7.834 X 10 ⁻¹
0.062	2.676 X 10 ⁻⁵	1.853 X 10 ⁻⁷	0.115	5.350 X 10 ⁻²	1.431 X 10 ⁻³	0.68	2.737 X 10 ⁻¹	7.963 X 10 ⁻¹
0.063	3.570 X 10 ⁻⁵	2.558 X 10 ⁻⁷	0.120	7.281 X 10 ⁻²	2.145 X 10 ⁻³	0.70	2.537 X 10 ⁻¹	8.083 X 10 ⁻¹
0.064	4.713 X 10 ⁻⁵	3.493 X 10 ⁻⁷	0.125	9.588 X 10 ⁻²	3.099 X 10 ⁻³	0.72	2.354 X 10 ⁻¹	8.194 X 10 ⁻¹
0.065	6.613 X 10 ⁻⁵	4.721 X 10 ⁻⁷	0.130	1.227 X 10 ⁻¹	4.336 X 10 ⁻³	0.74	2.185 X 10 ⁻¹	8.297 X 10 ⁻¹
0.066	7.984 X 10 ⁻⁵	6.319 X 10 ⁻⁷	0.135	1.530 X 10 ⁻¹	5.897 X 10 ⁻³	0.76	2.030 X 10 ⁻¹	8.392 X 10 ⁻¹
0.067	1.025 X 10 ⁻⁴	8.380 X 10 ⁻⁷	0.140	1.866 X 10 ⁻¹	7.822 X 10 ⁻³	0.78	1.888 X 10 ⁻¹	8.481 X 10 ⁻¹
0.068	1.305 X 10 ⁻⁴	1.101 X 10 ⁻⁶	0.145	2.232 X 10 ⁻¹	1.015 X 10 ⁻²	0.80	1.758 X 10 ⁻¹	8.564 X 10 ⁻¹
0.069	1.649 X 10 ⁻⁴	1.435 X 10 ⁻⁶	0.150	2.622 X 10 ⁻¹	1.290 X 10 ⁻²	0.82	1.638 X 10 ⁻¹	8.641 X 10 ⁻¹
0.070	2.066 X 10 ⁻⁴	1.856 X 10 ⁻⁶	0.155	3.032 X 10 ⁻¹	1.610 X 10 ⁻²	0.84	1.528 X 10 ⁻¹	8.713 X 10 ⁻¹
0.071	2.571 X 10 ⁻⁴	2.380 X 10 ⁻⁶	0.160	3.457 X 10 ⁻¹	1.979 X 10 ⁻²	0.86	1.426 X 10 ⁻¹	8.780 X 10 ⁻¹
0.072	3.176 X 10 ⁻⁴	3.030 X 10 ⁻⁶	0.165	3.892 X 10 ⁻¹	2.396 X 10 ⁻²	0.88	1.332 X 10 ⁻¹	8.843 X 10 ⁻¹
0.073	3.897 X 10 ⁻⁴	3.831 X 10 ⁻⁶	0.170	4.332 X 10 ⁻¹	2.862 X 10 ⁻²	0.90	1.246 X 10 ⁻¹	8.901 X 10 ⁻¹
0.074	4.751 X 10 ⁻⁴	4.810 X 10 ⁻⁶	0.175	4.772 X 10 ⁻¹	3.379 X 10 ⁻²	0.92	1.166 X 10 ⁻¹	8.956 X 10 ⁻¹
0.075	5.757 X 10 ⁻⁴	5.999 X 10 ⁻⁶	0.180	5.208 X 10 ⁻¹	3.946 X 10 ⁻²	0.94	1.093 X 10 ⁻¹	9.007 X 10 ⁻¹
0.076	6.934 X 10 ⁻⁴	7.436 X 10 ⁻⁶	0.185	5.636 X 10 ⁻¹	4.561 X 10 ⁻²	0.96	1.024 X 10 ⁻¹	9.055 X 10 ⁻¹
0.077	8.304 X 10 ⁻⁴	9.162 X 10 ⁻⁶	0.190	6.053 X 10 ⁻¹	5.225 X 10 ⁻²	0.98	9.613 X 10 ⁻²	9.100 X 10 ⁻¹
0.078	9.891 X 10 ⁻⁴	1.122 X 10 ⁻⁵	0.195	6.455 X 10 ⁻¹	5.935 X 10 ⁻²	1.0	9.029 X 10 ⁻²	9.143 X 10 ⁻¹
0.079	1.172 X 10 ⁻³	1.367 X 10 ⁻⁵	0.200	6.840 X 10 ⁻¹	6.690 X 10 ⁻²	1.1	6.679 X 10 ⁻²	9.319 X 10 ⁻¹
0.080	1.382 X 10 ⁻³	1.657 X 10 ⁻⁵	0.22	8.169 X 10 ⁻¹	1.011 X 10 ⁻¹	1.2	5.035 X 10 ⁻²	9.451 X 10 ⁻¹
0.081	1.621 X 10 ⁻³	1.997 X 10 ⁻⁵	0.24	9.126 X 10 ⁻¹	1.405 X 10 ⁻¹	1.3	3.862 X 10 ⁻²	9.551 X 10 ⁻¹
0.082	1.893 X 10 ⁻³	2.395 X 10 ⁻⁵	0.26	9.712 X 10 ⁻¹	1.834 X 10 ⁻¹	1.4	3.007 X 10 ⁻²	9.629 X 10 ⁻¹
0.083	2.201 X 10 ⁻³	2.859 X 10 ⁻⁵	0.28	9.972 X 10 ⁻¹	2.282 X 10 ⁻¹	1.5	2.375 X 10 ⁻²	9.690 X 10 ⁻¹
0.084	2.548 X 10 ⁻³	3.398 X 10 ⁻⁵	0.30	9.971 X 10 ⁻¹	2.736 X 10 ⁻¹	1.6	1.899 X 10 ⁻²	9.738 X 10 ⁻¹
0.085	2.938 X 10 ⁻³	4.020 X 10 ⁻⁵	0.32	9.771 X 10 ⁻¹	3.185 X 10 ⁻¹	1.7	1.536 X 10 ⁻²	9.777 X 10 ⁻¹
0.086	3.373 X 10 ⁻³	4.735 X 10 ⁻⁵	0.34	9.432 X 10 ⁻¹	3.621 X 10 ⁻¹	1.8	1.255 X 10 ⁻²	9.808 X 10 ⁻¹
0.087	3.859 X 10 ⁻³	5.555 X 10 ⁻⁵	0.36	8.999 X 10 ⁻¹	4.040 X 10 ⁻¹	1.9	1.035 X 10 ⁻²	9.834 X 10 ⁻¹
0.088	4.397 X 10 ⁻³	6.491 X 10 ⁻⁵	0.38	8.512 X 10 ⁻¹	4.438 X 10 ⁻¹	2.0	8.612 X 10 ⁻³	9.856 X 10 ⁻¹
0.089	4.993 X 10 ⁻³	7.556 X 10 ⁻⁵	0.40	7.997 X 10 ⁻¹	4.813 X 10 ⁻¹			
0.090	5.651 X 10 ⁻³	8.763 X 10 ⁻⁵	0.42	7.475 X 10 ⁻¹	5.164 X 10 ⁻¹			

Total Blackbody Radiation

T, K	$\int_0^\infty W d\lambda$, W/cm ²	$W_{\max}(T)$, W/(cm ² °μm)	T, K	$\int_0^\infty W d\lambda$, W/cm ²	$W_{\max}(T)$, W/(cm ² °μm)	T, K	$\int_0^\infty W d\lambda$, W/cm ²	$W_{\max}(T)$, W/(cm ² °μm)
1	5.679 X 10 ⁻¹²	1.290 X 10 ⁻¹⁵	140	2.181 X 10 ⁻³	6.936 X 10 ⁻⁵	300	4.600 X 10 ⁻²	3.134 X 10 ⁻³
5	3.549 X 10 ⁻⁹	4.030 X 10 ⁻¹²	150	2.875 X 10 ⁻³	9.794 X 10 ⁻⁵	310	5.245 X 10 ⁻²	3.692 X 10 ⁻³
10	5.679 X 10 ⁻⁸	1.290 X 10 ⁻¹⁰	160	3.722 X 10 ⁻³	1.352 X 10 ⁻⁴	320	5.955 X 10 ⁻²	4.328 X 10 ⁻³
15	2.875 X 10 ⁻⁷	9.794 X 10 ⁻¹⁰	170	4.743 X 10 ⁻³	1.831 X 10 ⁻⁴	330	6.735 X 10 ⁻²	5.047 X 10 ⁻³
20	9.086 X 10 ⁻⁷	4.127 X 10 ⁻⁹	180	5.961 X 10 ⁻³	2.437 X 10 ⁻⁴	340	7.589 X 10 ⁻²	5.860 X 10 ⁻³
30	4.600 X 10 ⁻⁶	3.134 X 10 ⁻⁸	190	7.401 X 10 ⁻³	3.194 X 10 ⁻⁴	350	8.522 X 10 ⁻²	6.774 X 10 ⁻³
40	1.454 X 10 ⁻⁵	1.321 X 10 ⁻⁷	200	9.086 X 10 ⁻³	4.127 X 10 ⁻⁴	360	9.538 X 10 ⁻²	7.799 X 10 ⁻³
50	3.549 X 10 ⁻⁵	4.030 X 10 ⁻⁷	210	1.105 X 10 ⁻²	5.267 X 10 ⁻⁴	370	1.065 X 10 ⁻¹	8.944 X 10 ⁻³
60	7.360 X 10 ⁻⁵	1.003 X 10 ⁻⁶	220	1.331 X 10 ⁻²	6.647 X 10 ⁻⁴	380	1.184 X 10 ⁻¹	1.022 X 10 ⁻²
70	1.364 X 10 ⁻⁴	2.168 X 10 ⁻⁶	230	1.590 X 10 ⁻²	8.301 X 10 ⁻⁴	390	1.314 X 10 ⁻¹	1.164 X 10 ⁻²
80	2.326 X 10 ⁻⁴	4.226 X 10 ⁻⁶	240	1.885 X 10 ⁻²	1.027 X 10 ⁻³	400	1.454 X 10 ⁻¹	1.321 X 10 ⁻²
90	3.726 X 10 ⁻⁴	7.616 X 10 ⁻⁶	250	2.218 X 10 ⁻²	1.260 X 10 ⁻³	410	1.605 X 10 ⁻¹	1.494 X 10 ⁻²
100	5.679 X 10 ⁻⁴	1.290 X 10 ⁻⁵	260	2.595 X 10 ⁻²	1.532 X 10 ⁻³	420	1.768 X 10 ⁻¹	1.686 X 10 ⁻²
110	8.315 X 10 ⁻⁴	2.077 X 10 ⁻⁵	270	3.018 X 10 ⁻²	1.851 X 10 ⁻³	430	1.942 X 10 ⁻¹	1.896 X 10 ⁻²
120	1.178 X 10 ⁻³	3.209 X 10 ⁻⁵	280	3.491 X 10 ⁻²	2.220 X 10 ⁻³	440	2.128 X 10 ⁻¹	2.127 X 10 ⁻²
130	1.622 X 10 ⁻³	4.789 X 10 ⁻⁵	290	4.017 X 10 ⁻²	2.645 X 10 ⁻³	450	2.328 X 10 ⁻¹	2.380 X 10 ⁻²

T, K	$\int_0^\infty W d\lambda, W/cm^2$	$W_{max}(T), W/(cm^2 \cdot \mu m)$	T, K	$\int_0^\infty W d\lambda, W/cm^2$	$W_{max}(T), W/(cm^2 \cdot \mu m)$	T, K	$\int_0^\infty W d\lambda, W/cm^2$	$W_{max}(T), W/(cm^2 \cdot \mu m)$
460	2.542×10^{-1}	2.656×10^{-2}	1180	11.01	2.951	1940	80.44	35.44
470	2.771×10^{-1}	2.958×10^{-2}	1200	11.78	3.209	1960	83.81	37.31
480	3.015×10^{-1}	3.286×10^{-2}	1220	12.58	3.486	1980	87.29	39.25
490	3.274×10^{-1}	3.643×10^{-2}	1240	13.43	3.781	2000	90.86	41.27
500	3.549×10^{-1}	4.030×10^{-2}	1260	14.32	4.096	2100	110.5	52.67
520	4.152×10^{-1}	4.904×10^{-2}	1280	15.25	4.431	2200	133.1	66.47
540	4.829×10^{-1}	5.922×10^{-2}	1300	16.22	4.789	2300	159.0	83.01
560	5.585×10^{-1}	7.103×10^{-2}	1320	17.25	5.169	2400	188.5	102.7
580	6.426×10^{-1}	8.465×10^{-2}	1340	18.32	5.572	2500	221.8	126.0
600	7.360×10^{-1}	1.003×10^{-1}	1360	19.43	6.001	2600	259.5	153.2
620	8.392×10^{-1}	1.182×10^{-1}	1380	20.59	6.455	2700	301.8	185.1
640	9.527×10^{-1}	1.385×10^{-1}	1400	21.81	6.936	2800	349.1	222.0
660	1.087	1.615×10^{-1}	1420	23.09	7.446	2900	401.7	264.5
680	1.215	1.875×10^{-1}	1440	24.42	7.986	3000	460.0	313.4
700	1.364	2.168×10^{-1}	1460	25.80	8.556	3100	524.5	369.2
720	1.527	2.496×10^{-1}	1480	27.24	9.158	3200	595.5	432.8
740	1.703	2.862×10^{-1}	1500	28.75	9.794	3300	673.5	504.7
760	1.895	3.270×10^{-1}	1520	30.31	10.46	3400	758.9	586.0
780	2.102	3.724×10^{-1}	1540	31.94	11.17	3500	852.2	677.4
800	2.326	4.226×10^{-1}	1560	33.63	11.92	3600	953.8	779.9
820	2.567	4.782×10^{-1}	1580	35.39	12.70	3700	1065	894.4
840	2.827	5.394×10^{-1}	1600	37.22	13.52	3800	1184	1022
860	3.106	6.667×10^{-1}	1620	39.12	14.39	3900	1314	1164
880	3.406	6.806×10^{-1}	1640	41.08	15.30	4000	1454	1321
900	3.726	7.616×10^{-1}	1660	43.12	16.26	4500	2328	2380
920	4.069	8.500×10^{-1}	1680	45.24	17.26	5000	3549	4030
940	4.434	9.465×10^{-1}	1700	47.43	18.31	5500	5197	6491
960	4.824	1.052	1720	49.71	19.42	6000	7360	10030
980	5.239	1.166	1740	52.06	20.57	6500	10140	14960
1000	5.679	1.290	1760	54.50	21.78	7000	13640	21680
1020	6.147	1.424	1780	57.01	23.05	7500	17970	30610
1040	6.644	1.569	1800	59.61	24.37	8000	23260	42260
1060	7.170	1.726	1820	62.31	25.75	8500	29640	57230
1080	7.726	1.895	1840	65.09	27.20	9000	37260	76160
1100	8.315	2.077	1860	67.97	28.71	9500	46260	99800
1120	8.937	2.273	1880	70.94	30.29	10000	56790	12900
1140	9.591	2.483	1900	74.01	31.94			
1160	10.29	2.709	1920	77.18	33.65			

Total Emittance

Material	Temperature, K	Type*	Total † emittance
Aluminum:			
Polished	370-630	h	0.04-0.06
Heavily oxidized	360-800	h	0.2-0.33
Electrolytically oxid., 4-10 μm thick	310	h	0.72-0.83
Aluminum oxide	80-500	n	0.76-
	1200-1750		0.45-0.41
Aluminum oxide layer:			
0.25 μm thick	311	n	0.06
0.50 μm thick	311	n	0.11
1.0 μm thick	311	n	0.30
2.0 μm thick	311	n	0.65
3.0 μm thick	311	n	0.70
4.0 μm thick	311	n	0.70
7.0 μm thick	311	n	0.75
Antimony:			
Polished	300-350	n	0.28-0.31
Beryllium	1100-1300-1480	n	0.41-0.57-0.87
Bismuth	350		0.34
Brass:			
Highly polished	500-610	h	0.02
Polished	373	n	0.06
Oxidized	450-590	n	0.56-0.64
Bronze, 4-7 aluminum:			
Polished	450-1270	n	0.03-0.06
Oxidized	450-1270	n	0.08-0.16
Cadmium	80-300	h	0.03
Carbon:			
Rough	1200-2000	n	0.84-0.81
Polished	1200-2000	n	0.82-0.79

* n = normal (emittance), h = hemispherical (emittance). † The emittances correspond to the given temperatures. Linear interpolation between points fairly accurate

Material	Temperature, K	Type*	Total emittance
Ceria (cerium dioxide):			
Powder coating	670-1070-1350-2250	n	0.53-0.30-0.90-0.93
Heat treated	1300-1700-1900	h	0.65-0.40-0.50
Chromium	370-600-750-1220	n	0.06-0.10-0.42
	80	h	0.07
Cobalt	350-600-1030	n	0.20-0.28-0.74
Copper:			
Polished	80-800	h	0.02-0.03
Polished pure	300-700-970-1410	h	0.04-0.07-0.19-0.15
Oxidized	300-600-800-1100	h	0.38-0.47-0.59-0.87
Polished	80-380-1160	n	0.02-0.01-0.02
Oxidized	80-540-700-1078	n	0.66-0.78-0.90-0.93
Gold:			
Polished	80-1100	h	0.01-0.07
Graphite:			
ATJ	700-1400-2700	n	0.81-0.74-0.90
Pyrolytic, basal plane	1600-1800-2700	n	0.67-0.49-0.35
Pyrolytic, r plane	1570-1900-1900-2500	n	1.0-1.0-0.82
Pyrolytic film on ATJ	2000-2600	h	0.65-0.73
Iron and steel:			
Armco and pure, polished	160-1100	h	0.05-0.25
	600-1100	n	0.2-0.56
Cast, polished	300-915-1355	h	0.21-0.21-0.28
Cast, oxidized	360-800-1350	h	0.62-0.73-0.73
Wrought, smooth	300-1800	h	0.27
Smooth sheet, rolled	800-1350	h	0.48-0.60
Electrolytic, oxidized	310-700	h	0.78-
	1025-1800		0.89-0.94
Stainless steel 310	800-1400	h	0.25
Stainless steel 310 (grid blasted, oxidized)	400-1050	h	0.74-0.84
Stainless steel 347 (stably oxidized)	600-1400	h	0.86-0.91
Stainless steel 303 (stably oxidized)	600-1400	h	0.75-0.87
Stainless steel 18-8, polished oxidized	350-650	n	0.15-0.20
	350-650		0.84
Stainless steel, AISI 316	80-900	n	0.19-0.35-0.62-0.32
polished	1100-1300-1420		
Iron oxide, Fe ₂ O ₃	310-1350	h	0.82-0.89
Lead:			
Polished	310-530	h	0.04-0.08
Gray, oxidized	270-470	h	0.28
Oxidized at 473 K	473	h	0.63
Magnesium, polished	410-490	h	0.12
Manganin, bright, rolled	391	n	0.048
Mercury, pure, clean	273-373		0.09-0.12
Molybdenum:			
Vapor blasted	400-1800	h	0.07-0.21
Oxidized	600-810	h	0.81
Polished	1600-2300-2900	n	0.13-0.28-0.28
Oxidized	600-800	n	0.83
Nickel:			
Polished	80-1100	h	0.02-0.17
Polished	80-550-1450	n	0.07-0.04-0.19
Oxidized	420-700-980	n	0.07-0.39-0.47
Nickel-chromium Alloys:			
Inconel X, stably oxidized	580-1370	h	0.89-0.93
Inconel X, polished	80-800-1200	h	0.06-0.12-0.23
René 41, oxidized	550-1350	n	0.78-0.87
Inconel-NBSA-418 coating	750-1250	n	0.68-0.64
Nichrome 80-20, oxidized	480-900-1200	h	0.62-0.67-0.78
Nickel-copper Alloys:			
K Monel 5700	80-900-1300	n	0.14-0.20-0.30
Monel 400	300	h	0.12
Nickel-molybdenum alloys:			
Haynes Alloy C, oxidized	580-1370	h	0.90-0.96
Inor-8, polished	340-1240	n	0.15-0.25
Niobium-tungsten alloys:			
90-10, polished	1970-2580	h	0.27
85-15, polished	1970-2580	h	0.26
Palladium	400-1520	n	0.02-0.17
Platinum, cold rolled	420-1500	n	0.02-0.16
	690-1700	h	0.09-0.17

Material	Temperature, K	Type*	Total emittance
Rhodium:			
As received	490-1520	n	0.02-0.09
Polished	420-1080-1250	n	0.012-0.068-0.034
Plated on stainless steel	80	h	0.075
Silver:			
Polished	650-1100	h	0.03-0.04
Thermally etched	460-1100	h	0.04-0.08
Tantalum:			
Polished, gas adsorbed	480-1480	h	0.1-0.25
Polished	1600-2920	h	0.17-0.30
Tantalum carbide, polished	1600-3000	n	0.2-0.33
Tantalum nitride, polished	800-1500	n	0.74-0.80-0.60
Tellurium	295	n	0.22
Tin, polished	310-360	h	0.05
Titanium:			
Polished	900	h	0.24
Electropolished	250-370	h	0.1-0.13
Titanium:			
Oxidized	640-950-1100	h	0.54-0.60
Oxidized, 306 hr at 813 K	360-700	n	0.35-0.48
Oxidized, 306 hr at 580 K	360-700	n	0.11-0.20
Titanium-aluminum alloy:			
A-110-AT, polished	80-600-1100	n	0.12-0.20-0.52
Titanium-manganese Alloys:			
C-110M, AMS 4908, polished	300-900	n	0.05-0.17
oxidized	300-900	n	0.50-0.61
RS-120, oxidized	600-1100	h	0.67-0.72
Tungsten:			
Polished	400-2000-3400	h	0.04-0.24-0.34
Polished	1400-3000	n	0.15-0.32
Filament	300-2300	n	0.032-0.28
Uranium	1200	h	0.35
Zinc:			
Pure, polished	300-530	n	0.02-0.06
Oxidized	300-470-800	n	0.28-0.14-0.11
Zirconium, as received	1150-1250-1450-1860	n	0.33-0.39-0.26-0.32
Water	273-373	n	0.92-0.96
Ice:			
Smooth, H ₂ O	273	n	0.96
Rough crystals	273	n	0.985
Glass	293	n	0.94
Lacquer:			
White	373	n	0.925
Black matte	373	n	0.97
Oil paints, all colors	273-373	n	0.92-0.96
Enamel	295	n	0.90-0.95
Candle soot	273-373	n	0.952
Plaster	273-373	n	0.91
Paper	373	n	0.92
Rubber, hard, glossy plate	297	n	0.945
Quartz (fused)	295	n	0.932

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Interpretation of Interferograms

In order to interpret an interferogram, it is first necessary to know the interferogram scale factor, i.e., the quantitative relation defining the correspondence between a fringe spacing on the interferogram and the parameter of interest. The interferogram scale factor is determined by the fact that the space between fringes of like nature corresponds to an optical path difference of one wavelength between the measurement and reference wavefronts and by knowing the type of interferometric setup.

The commonly used interferometric setups can be categorized into one of two types, either the single-pass type or the double-pass type. In a single-pass interferometer, the measurement beam traverses the item under test only once. In a double-pass interferometer, however, the measurement beam traverses the item under test once and is then reflected back through the item under test a second time, usually by an auxiliary factor.

Therefore, for a single-pass transmitted wavefront measurement, e.g. the Mach-Zehnder, the interferogram scale factor is: one fringe spacing = 1λ , where λ is the wavelength used in the interferometer. However, when a reflecting surface, such as a plano mirror, is being evaluated at normal incidence the interferogram scale factor is: one fringe spacing = $\lambda/2$. The reason for this is that at normal incidence the reflected wavefront will have *twice* the error of the reflecting surface. Thus, when evaluating mirror surfaces at normal incidence, one fringe corresponds to one-half wavelength. Table 1 lists the interferogram scale factor for some common interferometric setups and for a variety of measured parameters as well.

In the case of a retroreflector or cube corner, the quantitative information with respect to wavefront distortion and angular deviation is contained in the output wavefront. This information can be extracted by comparing the output wavefront to a plane reference wavefront in either a Twyman-Green or modified Fizeau interferometer (see Figures 6 and 7). In this case, the interferogram scale factor is such that one fringe corresponds to one wavelength, since it is the wavefront and not the surface that is of interest to the interpreter.

TABLE 1. INTERFEROGRAM SCALE FACTORS FOR COMMON INTERFEROMETRIC SETUPS AND FOR A VARIETY OF MEASURED PARAMETERS

Measured Parameter	Interferometric Setup	Interferogram Scale Factor	Typical Example
Reflective Surface	Normal incidence, single pass	1 fringe spacing = $\lambda/2$	Figures 1 & 2
Reflective Surface	Angle of incidence = θ , single pass	1 fringe spacing = $\lambda/(2\cos\theta)$	Figure 3
Reflective Surface	Normal incidence, double pass	1 fringe spacing = $\lambda/4$	Figure 4
Reflective Surface	Angle of incidence = θ , double pass	1 fringe spacing = $\lambda/(4\cos\theta)$	Figure 5
Single-pass Transmitted Wavefront Distortion	Single pass	1 fringe spacing = 1λ	
Single-pass Transmitted Wavefront Distortion	Double pass	1 fringe spacing = $\lambda/2$	
Double-pass Transmitted Wavefront Distortion	Single pass	1 fringe spacing = 2λ	
Double-pass Transmitted Wavefront Distortion	Double pass	1 fringe spacing = 1λ	

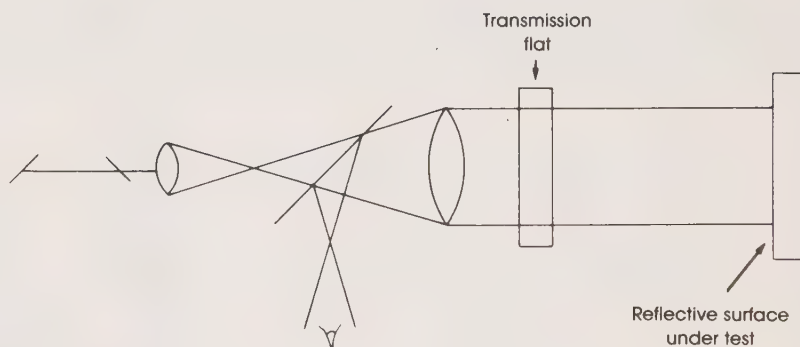


Figure 1.
Fizeau interferometer.

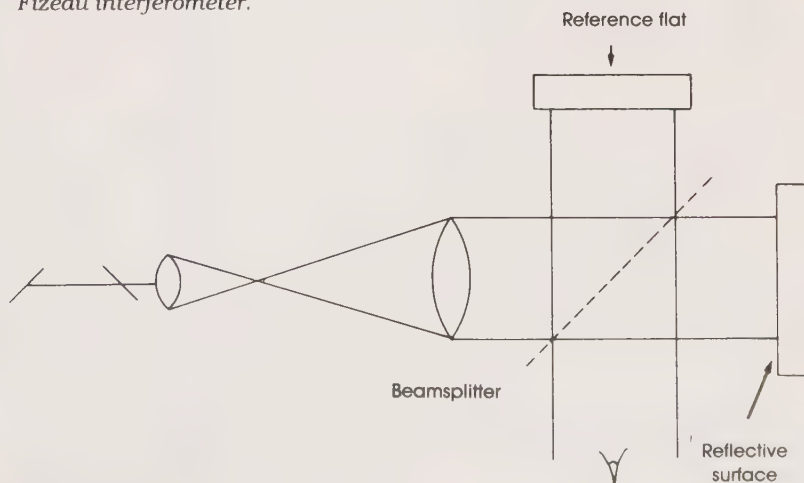


Figure 2.
Twyman-Green interferometer.

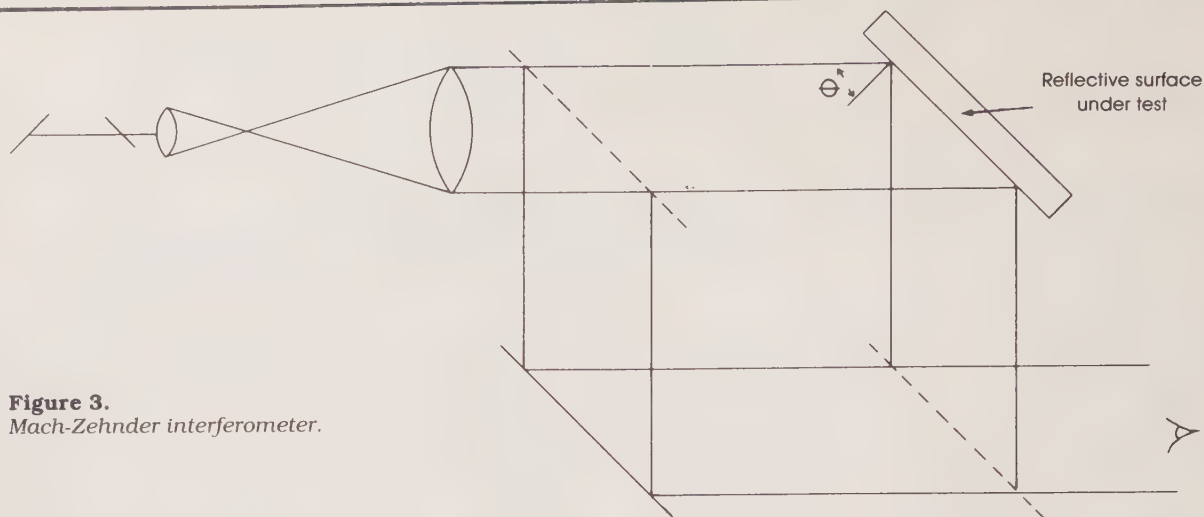


Figure 3.
Mach-Zehnder interferometer.

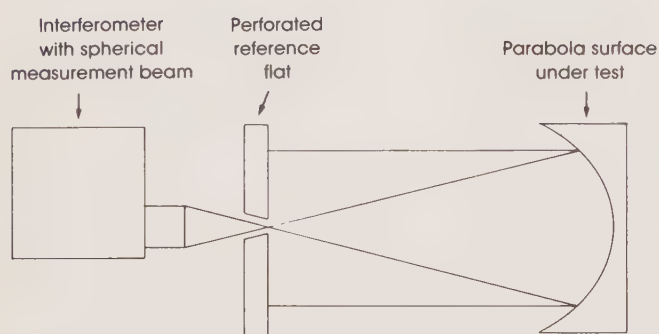


Figure 4.
Double-pass interferometer measuring
a parabolic surface.

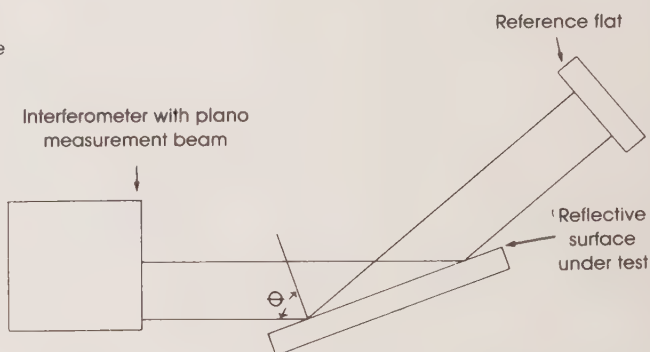


Figure 5.
Double-pass interferometer measuring
a flat reflective surface.

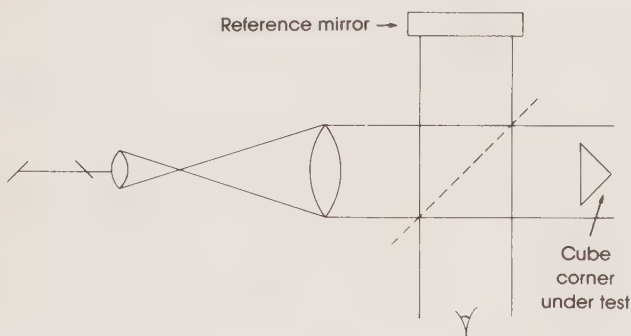


Figure 6.
Twyman-Green interferometer testing
a cube corner.

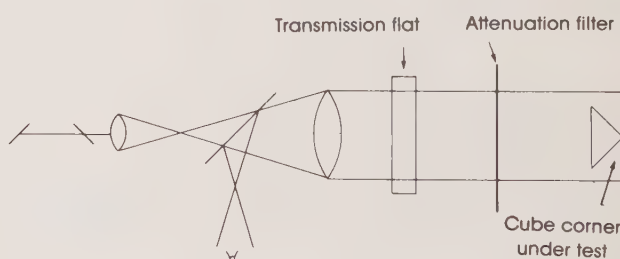


Figure 7.
Modified Fizeau interferometer testing
a cube corner.

Since a retroreflector acts like a mirror, and since mirror flatness is commonly evaluated using the one fringe corresponds to one-half wavelength interferogram scale factor, it is not uncommon to find retroreflectors which have been incorrectly evaluated because of the use of the incorrect interferogram scale factor.

Illustrative examples

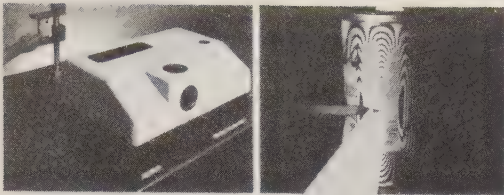
When two wavefronts of identical shape are perfectly superimposed,

uniphase interference, also commonly referred to as a fluffed-out fringe, will result (see Figures 8 and 9). It is difficult to extract visually quantitative information from the fluffed-out fringe. Nevertheless, quantitative information can be extracted from the fluffed-out fringe using photoelectric techniques. For example, distance-measuring interferometers are based on photoelectric sensing of the fluffed-out fringe. In addition, very flat Fizeau interfero-

meter surfaces are sometimes evaluated by a photoelectric evaluation of the fluffed-out fringe.

If a slight tilt is introduced between the two wavefronts, the resulting fringe pattern will be a family of parallel, equally-spaced straight fringes as shown in Figures 10 and 11. The number of fringes per unit length is a function of the tilt.

If a slight focus shift, i.e., optical power shift, is introduced between two interfering wavefronts of orig-



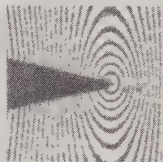
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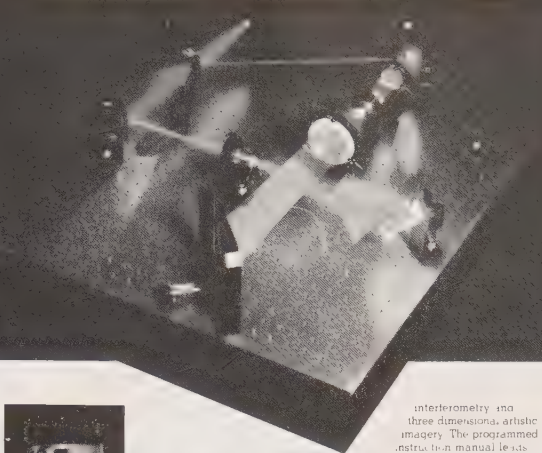
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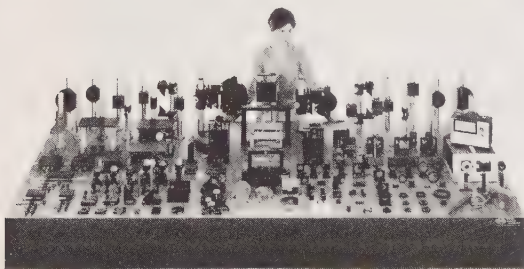
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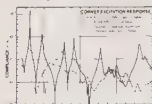
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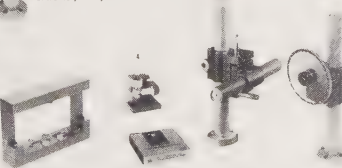
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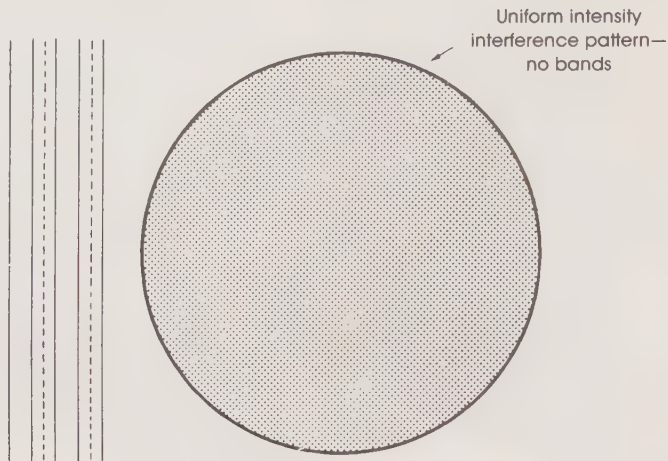


Figure 8.
Interference of plano wavefronts: no relative tilt.

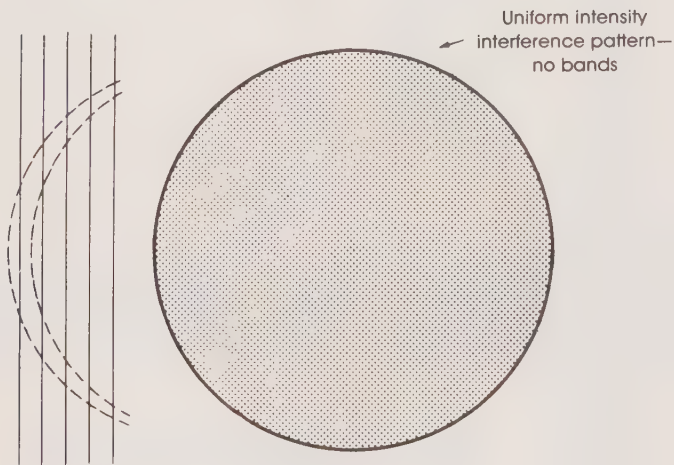


Figure 9.
Interference of two spherical wavefronts with same radius of curvature and no relative tilt.

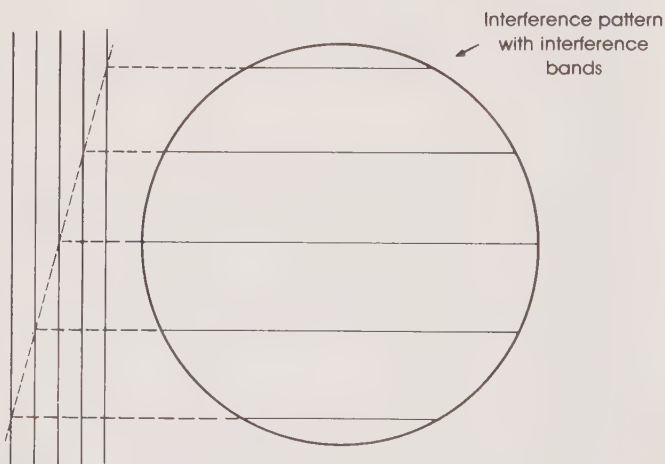


Figure 10.
Interference of plano waveforms with relative tilt.

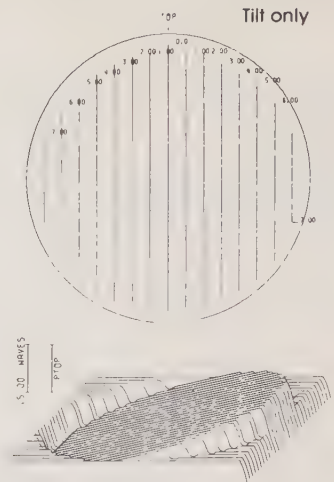


Figure 11.
Perfect test wavefront.

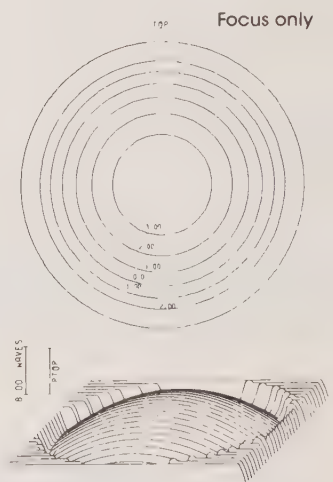


Figure 12.
Perfect test wavefront.

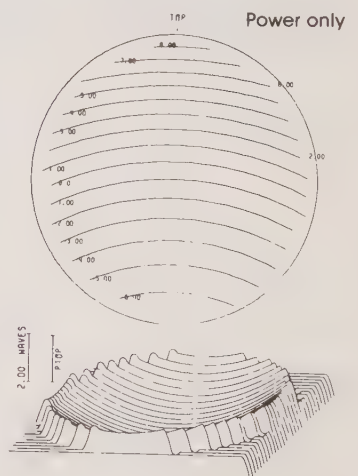
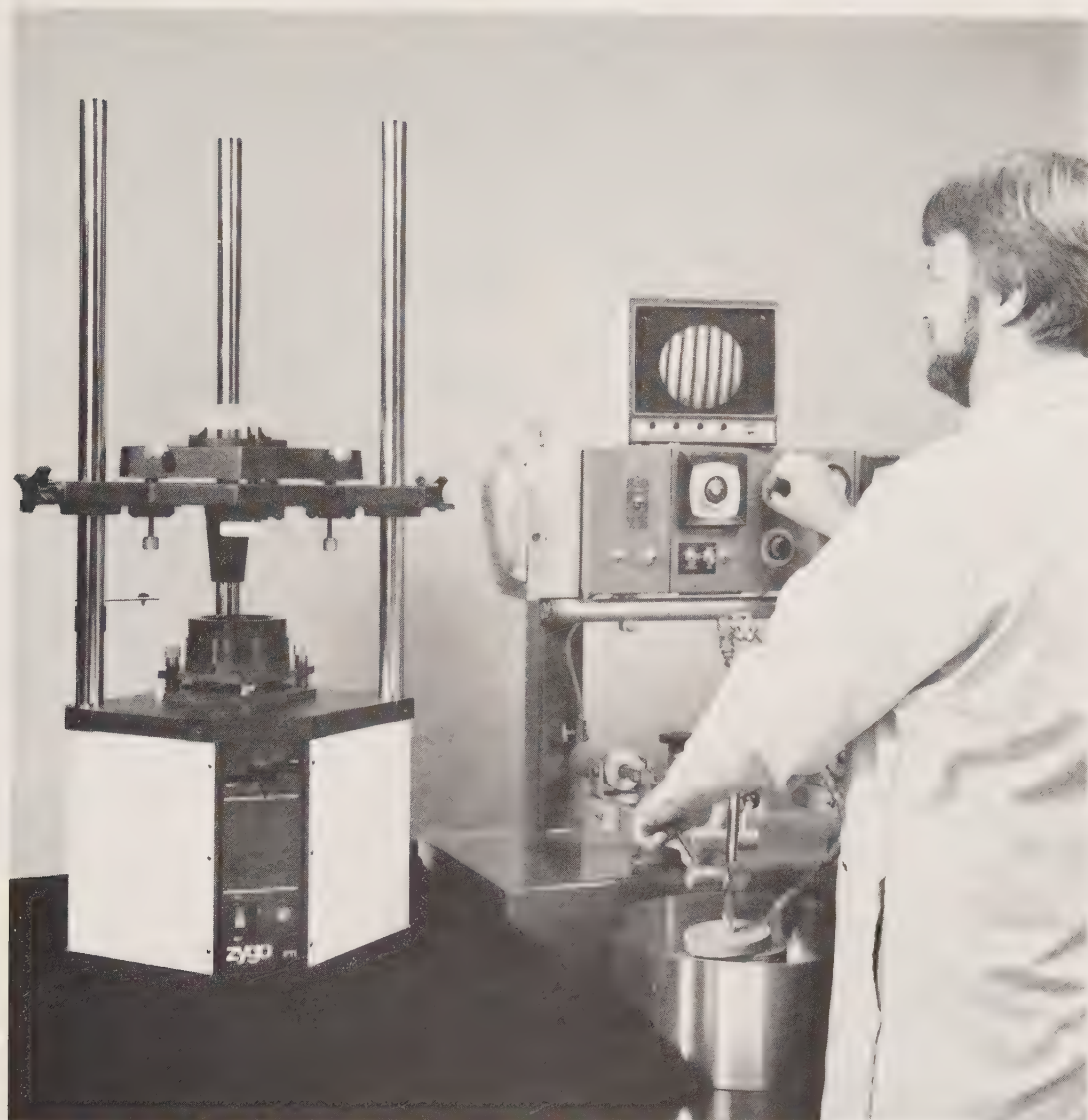


Figure 13.
Interference with slight tilt and power shift.

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inally identical shape, the resulting fringe pattern will be a family of concentric circles with nonuniform spacing as shown in Figure 12.

If both a slight tilt and a slight power shift are introduced between two interfering wavefronts of originally identical shape, the resulting fringe pattern will be a family of concentric circular arcs with non-uniform spacing as shown in Figure 13.

Phase information

A static interference pattern or interferogram alone contains no phase information, i.e., whether the distortion is a peak or valley. Since it is important not only when attempting to fabricate an optical element or surface but also when assembling optical systems to know whether the distortion corresponds to a peak or valley, the extraction of phase information is important. In order to ascertain phase information, it is necessary to ascertain and record the location of the zero order of the interference pattern. The zero order is located where there is zero optical path difference between the interfacing wavefronts. In order to locate the zero order, one can alter the interferometer cavity in a known way and note the direction of the motion of the fringes. Referring to Figure 14a, if the interferometer cavity spacing is decreased as shown, the fringes move away from the direction of the zero order. Conversely, if the interferometer cavity spacing is increased, the fringes move toward the zero order, Figure 14b.

Similarly, one can locate the zero order for nominally plane wavefronts by altering the tilt of the interferometer cavity or interfacing wavefronts in a known direction and by noting the direction of motion of the fringes. Referring to Figure 15, if the tilt is decreased as shown, the fringes move away from the direction of the zero order. Conversely, if the tilt is increased, the fringes move toward the zero order. Figure 16 illustrates the physical basis for this behavior.

In practice, it may not be possible to alter only one of the geometrical parameters of the interferometer cavity. When done manually, using both spacing and tilt of the cavity change, e.g. when one pushes on one element of the interferometer cavity, not only will the cavity spacing decrease but the tilt will, in general, also change in some unknown fashion about some unknown pivot point. Therefore, to ascertain unambiguously the direction of the zero order, it is necessary to observe and note 1) the change in fringe spacing and 2) the overall surface or wave-

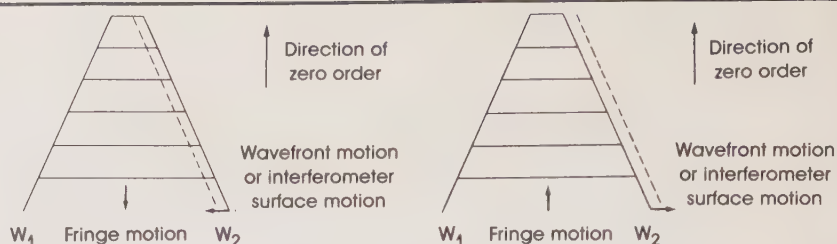


Figure 14a.
Effect of decreasing interferometer cavity spacing.

Figure 14b.
Effect of increasing interferometer cavity spacing.

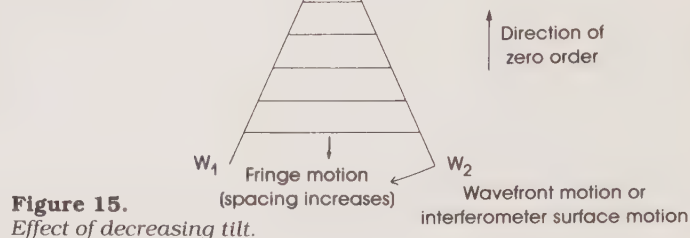


Figure 15.
Effect of decreasing tilt.

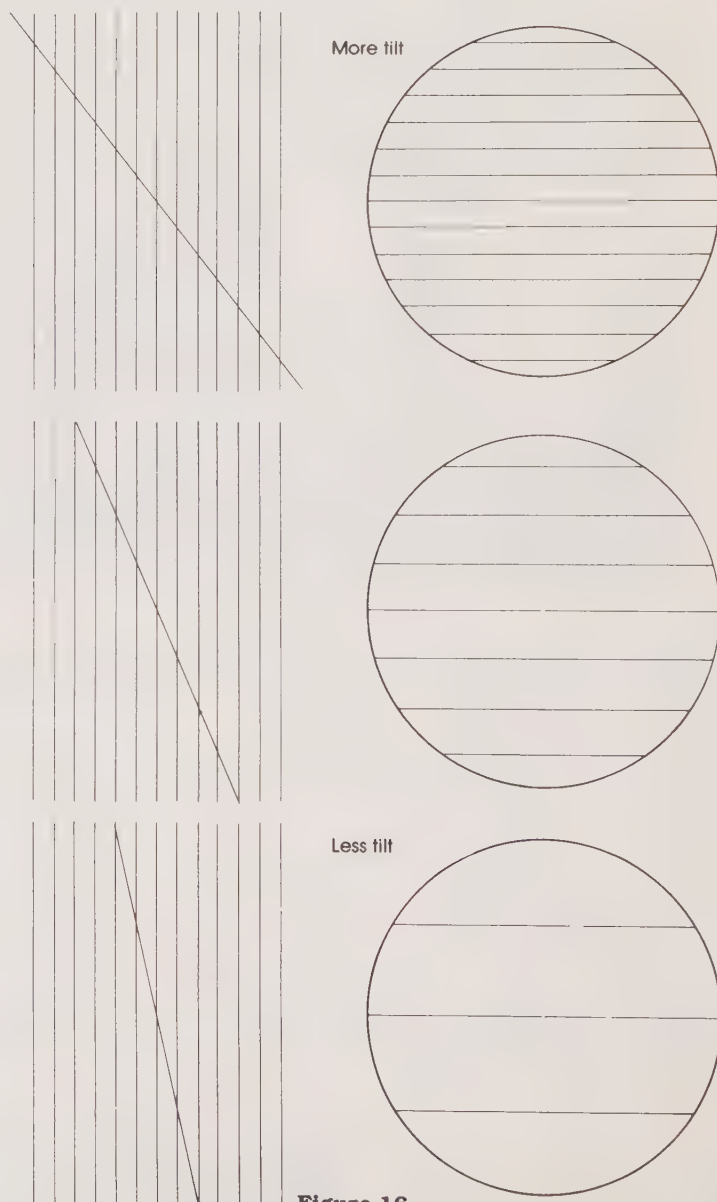


Figure 16.
Fringe spacing vs. tilt.

Interpretation of Interferograms

front geometry represented in the interference pattern in addition to the direction or directions of the fringe motion.

Fringe spacing is a measure of tilt (Figure 16). Therefore, changes in fringe spacing convey changes in tilt when the interferometer cavity geo-

metry is altered. An increase in fringe spacing indicates a decrease in tilt, and a decrease in fringe spacing indicates an increase in tilt.

It should be noted that the zero order may be located in more than a single direction. For example, with a concave cylindrical surface eval-

Test and Measurement

uated with zero tilt, the zero order is located in two directions, i.e., on opposite sides of the cylinder axis.

With a centered circular interference pattern, the fringes are formed by the path difference between two spherical wavefronts whose centers of curvature do not coincide. Coincidence implies the fluffed-out fringe condition described earlier. Consider one spherical wavefront to be the reference and the other the test wavefront. If the radius of the test wavefront is longer than the radius of the reference, the test wavefront will be convex to the reference (see Figure 17). When the radius of the test wavefront is shorter than that of the reference wavefront, the test wavefront will be concave to the reference (see Figure 18). If an adjustment is made to obtain coincidence of the two centers of curvature, the fringes in each case will appear to converge on the bull's-eye fringe. When the test wavefront is convex to the reference, the fringes curve toward the zero order and for the concave case away from it.

For the general case where the fringes are neither circular nor straight, a combination of these facts apply. First determine the direction of the zero order as described for straight fringes. Second, observe the direction the fringes curve relative to the zero order to determine whether the surface is convex or concave. This same rule applies for local distortions as well.

Figures 19 and 20 illustrate the technique commonly used to ascertain the nature of a spherical surface.

There may be cases where the above definitions of zero order do not strictly apply over the entire area of the interference pattern. For example, a fringe pattern consisting of a large number of local, enclosed fringes suggests a part with many localized hills and valleys. Determination of the phase of these distortions requires the examination of each one relative to the surrounding pattern using the appropriate definition for zero order. Simple tilt adjustments will cause the fringes to move in varying directions depending on the local error so that each one needs to be defined on the basis of the fringe motion nearest it.

Observing zero order whether it is local or global requires a dynamic adjustment. One must not lose sight of the fact that this adjustment, which changes the spacing, also changes the air wedge between the two surfaces under test. A change in spacing without a change in air wedge is virtually impossible to achieve. It is necessary in some cases to ascertain not only the direction in

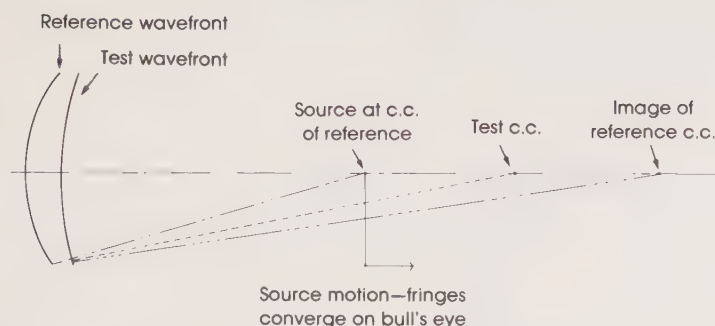


Figure 17.

Reference center of curvature (c.c.) inside focus.

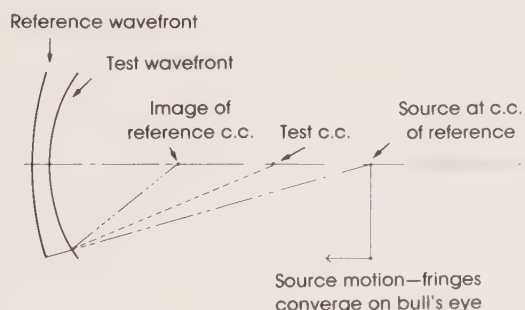
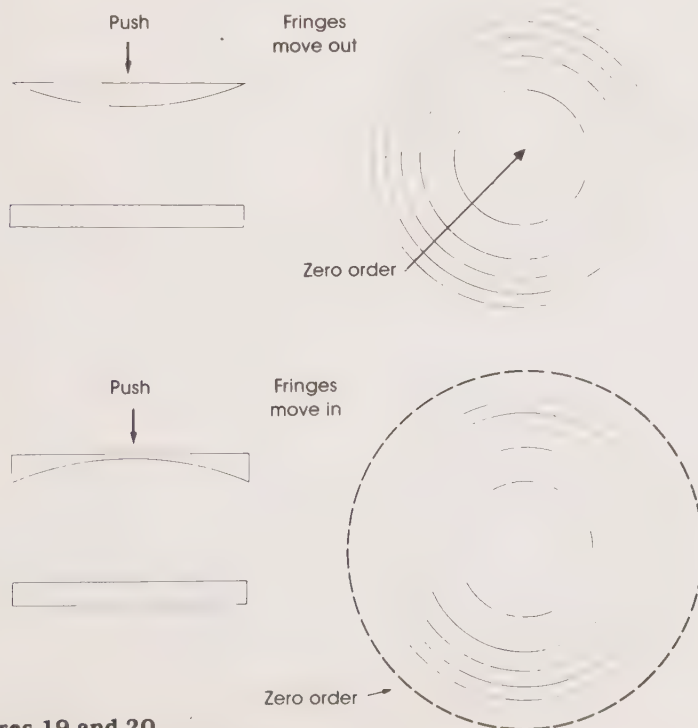


Figure 18.

Reference center of curvature (c.c.) outside focus.



Figures 19 and 20.

Measuring a spherical surface.

Test and Measurement

which the fringes are moving but also their relative spacing, since both changes may occur.

Generally the simple wedge change for the cases described above

will be the dominant change and the observed fringe pattern motion will follow the rules given. The above statements are given as a caution to those who may be testing highly un-

Interpretation of Interferograms

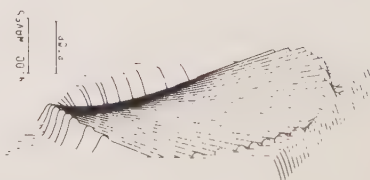
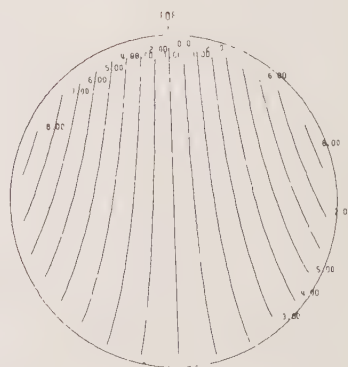
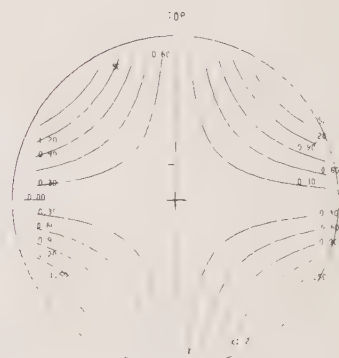
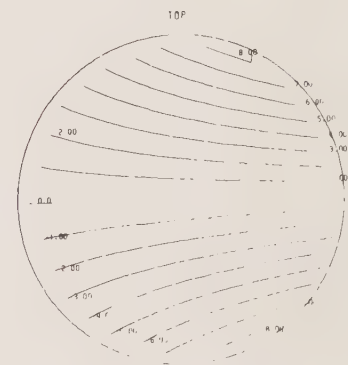
usual surfaces, and in those instances additional observations may be necessary when the dynamic adjustments have been made.

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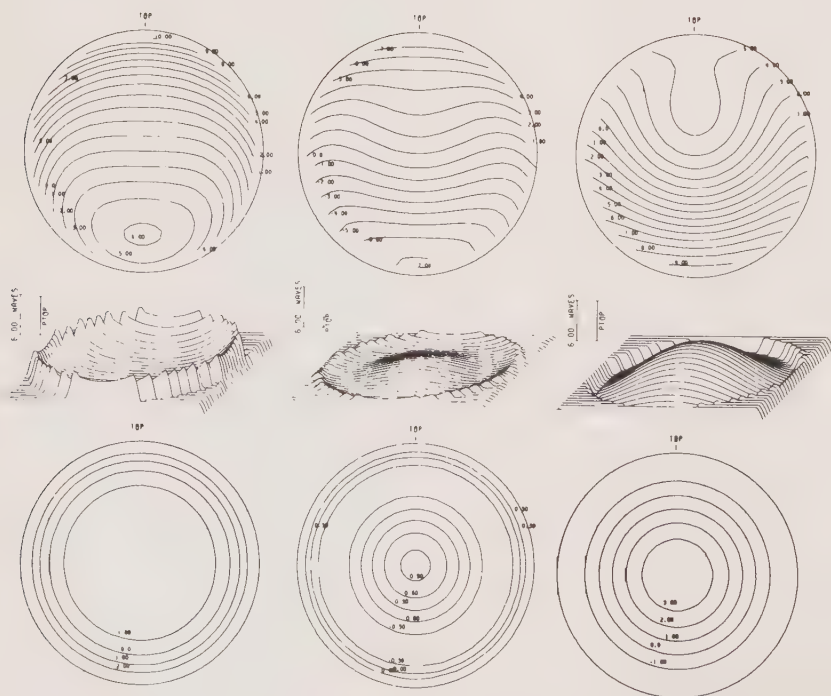
Interferograms Representing Individual and Combinations of Classical Aberrations



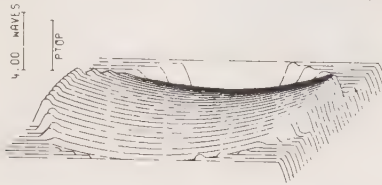
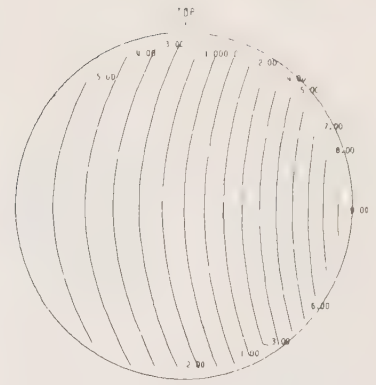
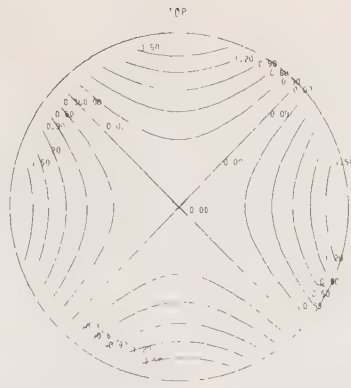
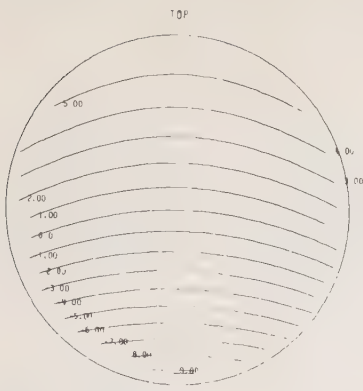
Spherical Aberration Best Focus



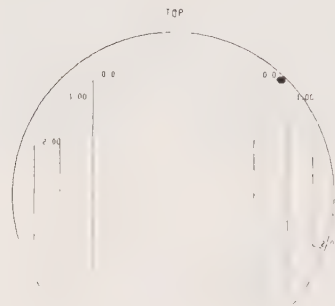
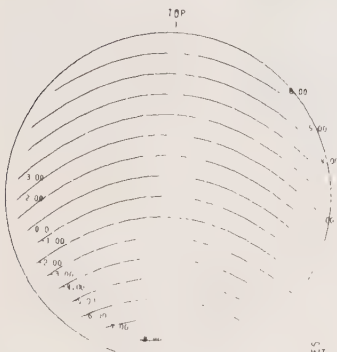
45-Degree Cylinder Best Focus



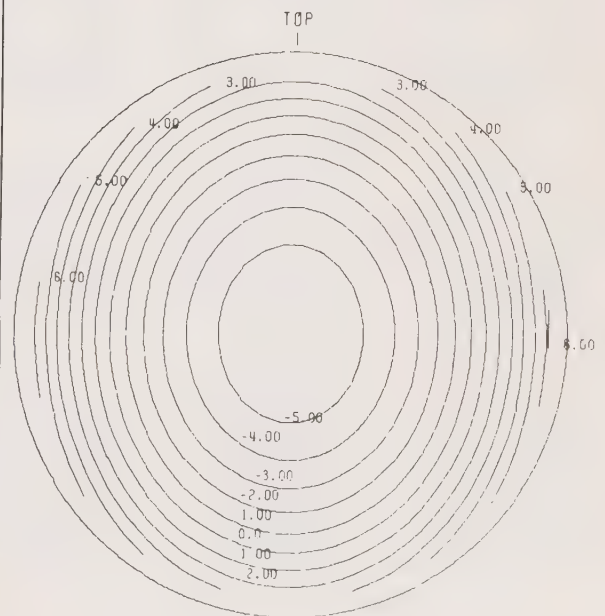
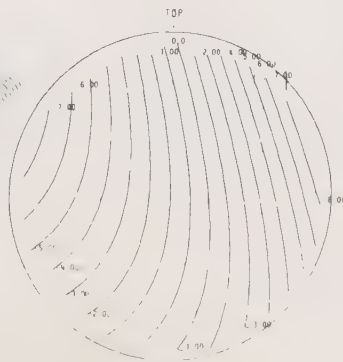
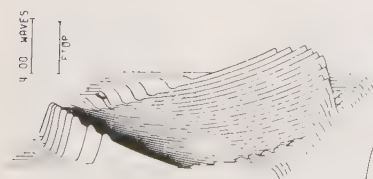
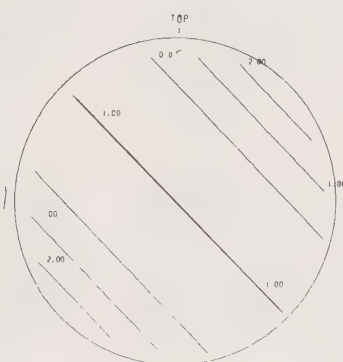
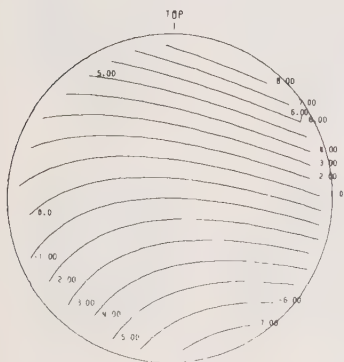
Spherical Aberration Focusing Effects



0-Degree Cylinder Best Focus

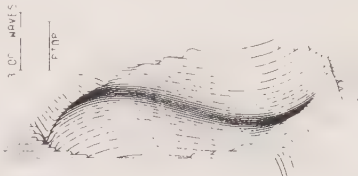
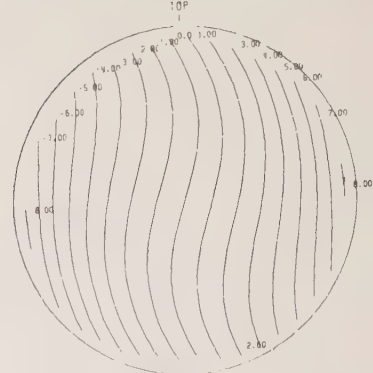
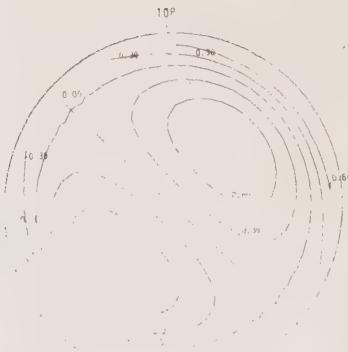
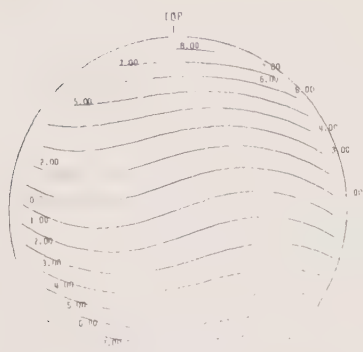


**0-Degree Cylinder
Principal Axis Focus**

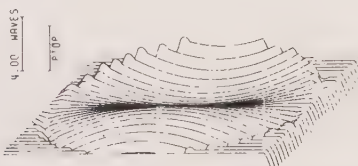
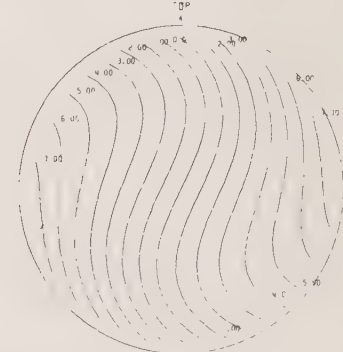
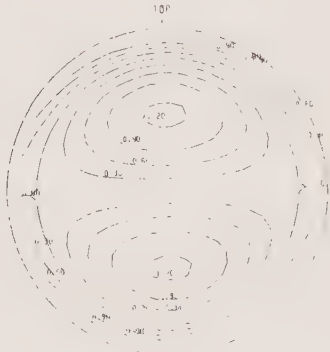
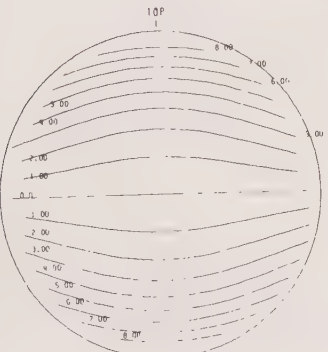


Bulls-eye with Cylinder

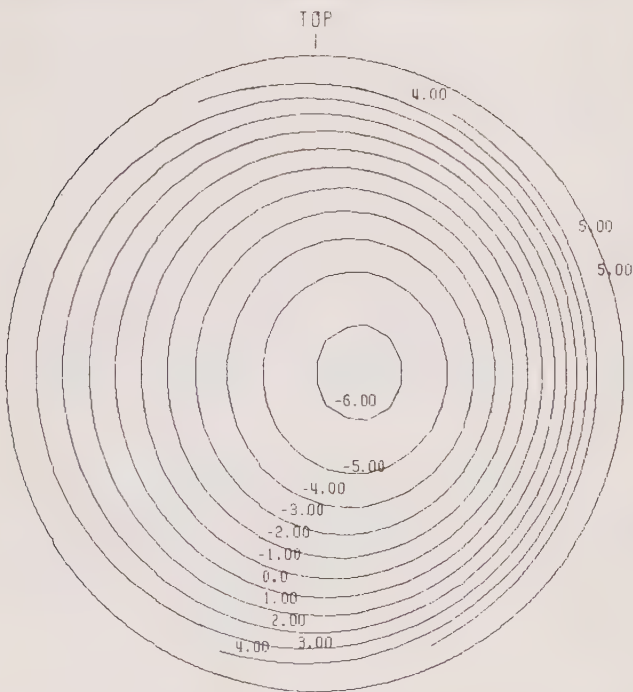
**45-Degree Cylinder
Principal Axis Focus**



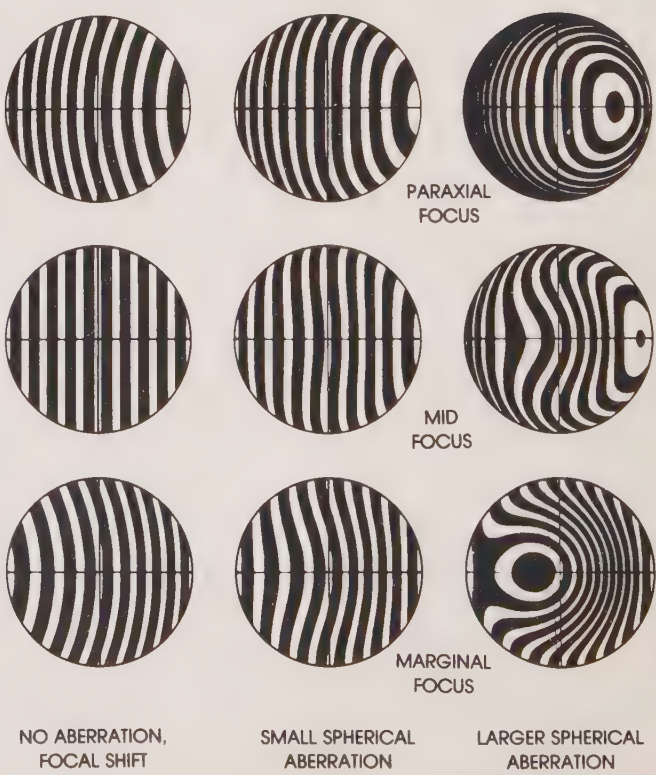
45-Degree Coma



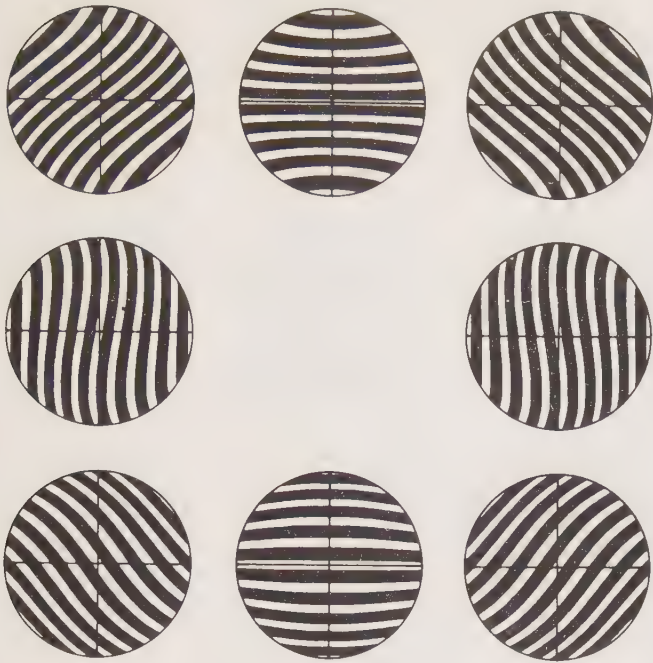
0-Degree Coma



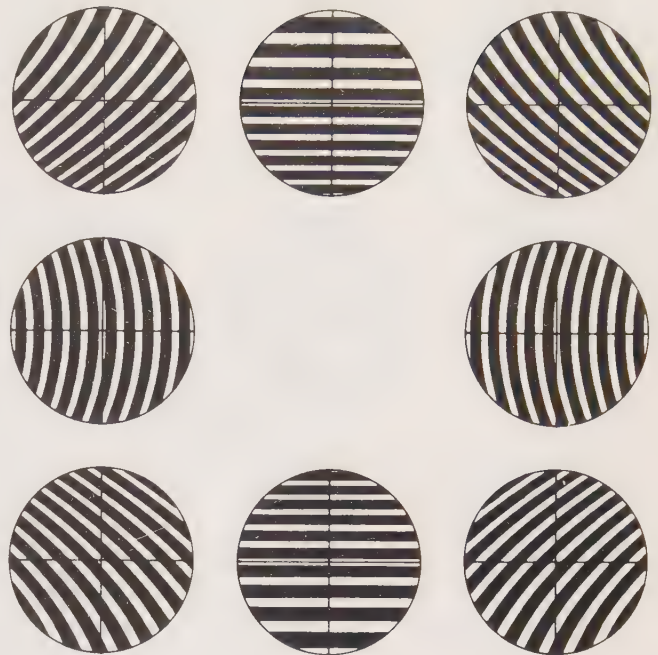
Bulls-eye with Coma



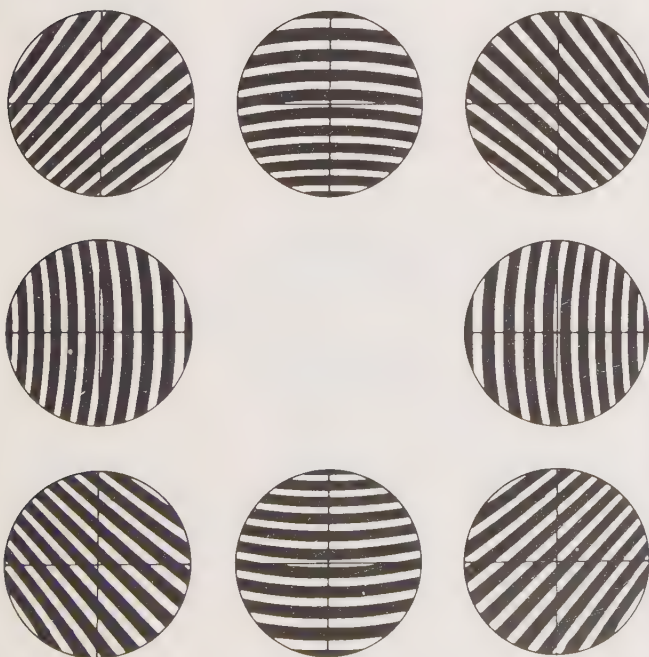
Interferograms, Spherical Aberration



Interferograms, Small Coma, Large Tilt



Interferograms,
Small Astigmatism, Sagittal Focus



Interferograms,
Small Astigmatism, Medial Focus



Interferograms, Large Coma, Large Tilt



Interferograms, Large Coma, Small Tilt

Interferograms, Large Astigmatism,
Sagittal Focus, Small TiltInterferograms, Large Astigmatism,
Medial Focus, Small Tilt

Interferograms, Small Focal Shift



COMA

SAGITTAL ASTIGMATISM

MEDIAL ASTIGMATISM

Acknowledgments

The computer-generated interferograms and wavefronts that appear in this section were provided by Ralph McDonough of the Itek Corporation and Professor Roland Shack of the Optical Sciences Center of the University of Arizona. We are grateful to them — and to the Zygo Corporation as well, of course — for permitting us to make use of this material.



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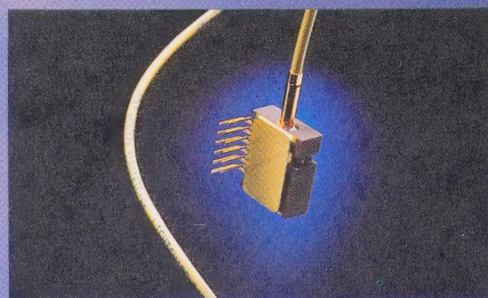
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